MASTER THESIS

MASTER IN INDUSTRIAL ENGINEERING

RAMMED EARTH AS A SUSTAINABLE BUILDING TECHNIQUE FOR AFFORDABLE RURAL CONSTRUCTION

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I, Pol Borràs Font, declare that this thesis titled, “Sustainable building technique for affordable rural construction: Rammed Earth” and the work presented in it are my own. I confirm that:

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- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
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ABSTRACT

Around the world, especially in rural areas, the most disadvantaged continue not to have access to proper house. Building environment has been stated as one of the main factors for health. Homeless people or those without appropriate one have 20 years less of life expectance and suffer 2 to 50 times more health issues than the rest of the population according to Doctors Without Borders. Housing has also influence in general wellbeing and is an indicator of development.

With the best purposes, governments, organizations and institutions have been finding ways to provide homes to different regions for the most needed. Despite all those efforts Habitat for Humanity estimated in 2015 that 1,6 billion of people around the world live in an “inadequate shelter”. Most of them live in rural areas so they have attired the attention in the last past years.

Furthermore, those organizations do not pay attention in the specific necessities such as the suitability of the proposed housing with the climate, or the integration of those new homes into the existing aggrupation. The initiatives usually consist to provide a few prototypic dwellings per zones, limited by the budget.

This thesis presents the process done so far, inside a project with the main objective to provide the rural village of Dewgain the knowledge of a new building tool technique, suitable to their specific necessities and climates, to empower the community people and make them actors of their own development. It is also continuity to the project initiated by the architect student Nicole C. Little from the University at Buffalo in collaboration with Live-in-Labs program of Amrita Vishwa Vidyapeetham. From her work Rammed Earth was designated as one of the possible solutions.

My participation in the project was initiated with one visit at the village, which was conducted for data and soil collection for analysis. The methodology and analysis are presented, which were set as a base to start designing the solution.

Based on the literature review, the analysis of the Dewgain soil was done to determine its suitability for the type of soil construction selected. Also a stabilizer was defined through methodic testing.

Since the project team had any experience on this kind of construction, a second visit was effectuate at the heart of the earth construction in India, Auroville (Tamil Nadu). The visit served up to get some advices for RE construction but also to know about alternative solutions for flooring and roofing.

Finally, a RE building prototype was designed and executed in the Ettimadai university campus of Amrita Vishwa Vidyapeetham as a previous stage to its application in Dewgain village, considering that it was necessary as a demonstration of the technique viability, but also as a testing site to proof its theoretical excellent properties.

Table of contents

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List of figures

List of tables

GLOSSARY

BRL	Building Research Laboratory
CSRE	Cement Stabilized Rammed Earth
LS	Linear Shrinkage
MDD	Maximum Dry Density
NGO	Non Governmental Organization
OMC	Optimum Moisture Content
OPC	Ordinary Portland Cement
PI	Plasticity Index
PSD	Particle Size Distribution
RE	Rammed Earth
SRE	Stabilized Rammed Earth
SREB	Stabilized Rammed Earth Blocks
SI	International System of Units
UCS	Unconfined Compression Strength
WC	Water Content

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1. INTRODUCTION

1.1.Motivation and project origin

Architectural design, Construction and its material choices are essential points for construction. These form the basis for housing and community development, main components for life and highly influential on wellbeing. The build environment is one of the major social and physical determinants of health, as stated by the World Health Organization, and has high impact on people's livelihood.

Housing challenges is a reality in many rural areas around India, especially those with extreme weather conditions as in the North of India. Most of the houses in those zones have been built using Adobe Technique, which requires a regular maintenance, suffers the thermite attacks and is not suitable for that specific climate. Furthermore, the architectural design for those houses has some limitations specially regarding the ventilation of houses.

To address the need of proper housing, government and NGOs have mostly relied on building concrete houses. Although it can be viewed as an efficient solution in the short term, it is not suitable for their climate and self-development.

The project titled: Alternative Architectural and Construction solutions for affordable housing in Villages using locally available materials and techniques was initiated by Dr. Anil Kumar Sharma and Amrita University, specially Live-in-Labs program. The main purpose of this project is to propose, analyze design, execute and teach a new construction method, Rammed earth in the Village of Dewgain (Jharkhand, India) to promote their development.

Research has been ongoing in the first part of the project to see how traditional techniques can be used along with other locally available materials to propose sustainable alternatives. After Amrita Researchers and students have been working on applying engineering techniques into traditional methods to improve the durability and solidity of the construction, Rammed Earth Technique has been determined as a solution suitable for that specific climate and accomplishing rest of housing challenges in that zone.

A part from the shared points with Amrita University, some personal motivations brought me to get into this project:

- Firstly, the opportunity to take part in a project which has a social impact and development of an Indian Rural community. Having direct interaction with villagers to learn from their life and experience, understanding their daily challenges and using engineering tools to provide some improvement in their lives has been the main source of motivation.
- Secondly, getting an engineering field work experience with daily challenges and issues to solve by collaborating with different Amrita organizations and actors involve as Ammachi Labs, Live-in-Labs and Amrita Campus staff has been also a great motivation to go on this project.
- Third, learning about sustainable construction techniques and solutions completely different that ones studied previously gave me some extra motivation to get into this domain.
- Finally, taking part in a 5 month international exchange program has been very rewarding for my personal experience. I've experienced the difference between two partnership institutions, Amrita Vishwa Vidyapheetham[1] and Universitat Politècnica[2] de Catalunya, in addition to cultural differences between two different Countries, Spain and India.

[1] https://www.amrita.edu/

[2] http://www.upc.edu/ca

1.2. Objectives

The main objective of the project is to provide to the Dewgain a new building tool, Rammed Earth, to empower them to be the actors of their own development.

In order to achieve the main objective, different sub-objectives are fixed in this phase pointing to the primary aim following a specific methodology. The sub-objectives need to be completed in the following order to ensure the next ones can be accomplished:

I. Write a complete state of the art of RE construction as well as other alternative techniques of construction for floor and roof solution.
II. Studying the applicability of RE using Dewgain local available soil via soil characterization and best binder determination.
III. Study of the Rammed Earth project feasibility through a prototype in Ettimadai Campus of Amrita University.
IV. Determine the Economical, Social, Environmental and Health impact of the application of RE technique in the Dewgain village to confirm the RE as a sustainable solution.

1.3. Scope of the project and limitations

- Cement is used as a stabilizer for the study
- Experimental studies on compression behavior have been confined to small scale prisms
- All the particles less than 4,75 mm in the soil have been taken for the study
- Scope of the project is limited to a prototype in Ettimadai Campus. The construction in Dewgain and study for application in other rural villages in India has to be studied at a later stage.

2. Start of the art

In this chapter an actual state of the art of rammed earth is presented looking over journal web sites and thesis, scientific reports, books and other articles.

Earth Housing is prehistorique, it even predates de development of the opposable thumb. The quest for shelter is in fact instinctive, and to the vast majority of the planet's species, shelter is earth [1]. For humans, earth has been used as a construction material in many ways since time immemorial. However, there are a few undesirable properties such as loss of strength when saturate with water, erosion due to wind or rain and poor dimensional stability.

For most buildings designers, rammed earth is an unfamiliar material and construction technique [2], as it is considered to be a non-standard, since its use in construction does not follow any industrial process.

Rammed Earth in english, *terre pisé* in French, *barro apisonado* or *tapial* in Spanish or Stampflehmbau in German is a construction method used primarily to build solid walls by compacting a precisa in progressive layers inside temporary Form [2]. It can be natural or stabilized with binders such as cement, calcium lime, natural fibers or ash. The main advantage of stabilizing the rammed earth is to increase its durability in front of water attack, to increase its mechanical performance (compressive strength), to reduce the shrinkage and to provide waterproof qualities.

The use of appropriate soil is the key to the success for rammed earth. Identifying the quality of a soil is essential. Not every soil is suitable for rammed Earth construction, but with some knowledge and experience most of the soils can be used. The topsoil and organics must be avoided. Then a (Auroville Earth Institute) precisely controlled mixture of gravel, sand, clay and silk is carefully proportioned, mixed to the correct moisture content, and then machine-compacted in a removable formwork to yield a dense, hard, stone-like wall [3].

In this chapter, the methods and tests for compaction in the laboratory and field are presented, as well as the ones commonly used to determine the physical and mechanical properties of the soil. At the end of the chapter some applications on real cases are presented in order to see its possibilities for use and its costs, in different parts of the world.

2.1. Benefits of Rammed Earth Construction

2.1.1. Sustainability

According to basic building material environmental classification by NIBE, various forms of earthen materials have the lowest environmental cost. Comparing rammed earth to alternative building materials as concrete and brick masonry, its embodied energy is significantly lower [4].

To calculate the environmental impact measurements such as the CO_2 Emissions and the embodied energy can be used. Buildings account for the 30 to 40 % of the total energy usage, according to the United Nations Energy usage.

The amount of energy required to produce a material and supply it to building construction site is called Embodied Energy. Embodied Energy mainly depends upon the maintenance cost of building, Manufacturing cost of building material and transportation cost. Embodied Energy and CO_2 emissions are presented in the following table [5]:

	Embodied Energy (MJ/Kg)
Concrete wall	5,600
Clay Brick wall	2,5
Concrete blocs wall	2,000
Dressing Stone wall	3,4
Mud	0,500
Rammed Earth	0,700

Table 2.1: Embodied energy of different types of constructions

2.1.2. Thermal Advantages

Rammed earth thick walls protect the inner space from external fluctuations of temperature because of its thermal inertia, meaning its slow reaction to temperature change [6].

Thermal mass is different from insulation although it has a similar consequence in the way it prevents heat to be transferred easily through the walls.

Thermal mass or thermal capacitance allows the heat to go through but very slowly because this material property enables the mass of a building to store heat. Thermal mass is effective in improving building comfort in any place that experiences a fluctuation of temperature during the day or season. For example If enough mass is used it can create a seasonal advantage. In summer the inner wall of a thermal mass will remain cool (it is nice to lean against it) and in winter it will remain warm (no cold radiation will emanate from it). Thermal mass works also to reduce the impact of the heat that penetrates inevitably through the doors and windows, which insulation cannot do. This combines with natural ventilation is very effective.

On the other hand Thermal insulation relies on many small vacuums in the insulating material that prevent the heat passing through the walls.

Insulation materials are useful in cold climates where the temperature remains low for many days. Thermal mass materials like rammed earth are also more appropriate for climates where the average temperature remains comfortable despite strong contrasts between day and nights, like generally in arid climates, like Dewgain semi-arid one. Rammed earth is important also in more humid season, like monsoon, to protect the walls from heavy rains.

2.1.3. Economical advantages

Rammed earth buildings necessitate basically materials or tools that can be found in the nature. It is easily accessible for people who do not have access to cash or who normally would not have enough money to invest in a building. This means that people become completely free and independent from market pressure, prices and necessity for accessing money [6].

This way of building becomes a powerful way to empower people in poor communities or zones where so many people have no access to decent dwellings.

On the other hand, the quantity of money that would be invested in a concrete or brick structure has to be supplied by an important labor work in order to transform natural material into a building.

2.2.Natural Rammed Earth Construction

Organic matter content should be avoided, as it may lead to high shrinkage, possible biodegradation as well as increasing susceptibility attack [7]. Also these organic matter biodegrades, absorbs water and is highly compressible. The use of top soil must be limited to 1 or 2% of the total mass of the soil [8].

2.2.1. Characterization of soil

The construction with rammed earth technique has a sense only if the soil is collected locally on the building site or nearby. If local soil is not suitable for rammed earth technique (because it's too sandy or too clayey), some complementary soil has to be brought it and occasionally bought, with the consequence of more costs related. Then the purpose of using rammed earth, which is to be ecological, low cost and in harmony with nature is not fulfilled.

To identify the properties of a soil some Laboratory tests are required. This tests follow the four fundamental properties of earth.

2.2.1.1. Particle Size Analysis

Soil is the result of the transformation of the underlying rock under the influence of a range of physical, chemical and biological processes related to biological and climatic conditions and to animal and plant life [3]. There are four main particles in the subsoil and these fragments range in size from gravel through sand, clay and silt. The relative proportions of these constituents play an important role in the performance of the material.

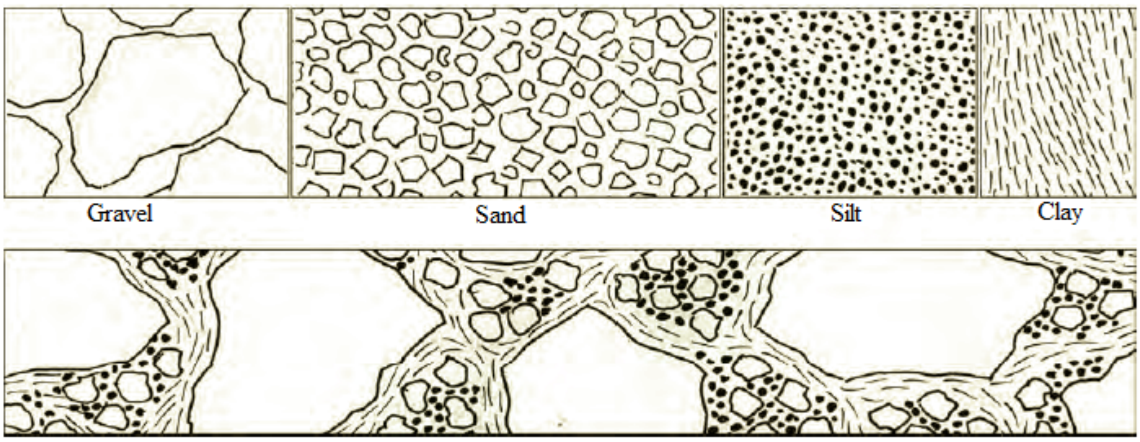

Figure 2.1: Particle size representation in RE [7]

According to ASTM-AFNOR, the grain size classification adopted by larger number of laboratories, it follows the next standards:

Gravel	Sand	Clay	Silt
More than 2 mm	2 mm to 0.06 mm	0.06 to 0.002 mm	Less than 0.002 mm

Table 2.2: Size grain of main soil components

According to the percentage of the four solid components (gravel, sand, silt and clay), the soil will be classified as: gravely, sandy, silty or clayey soil. A wide variety of sub-soils have been used for natural rammed earth buildings, with the exception of uniform coarse sands and gravels with no fines, as no external cementing agent is used [3].

In order to increase the mechanical strength and the weathering resistance of this natural type of construction the voids must be minimized. Any vacuum, as small as it can be, can weaken the structure. The best suitable soil is composed of different sizes of granulometry that allows de bigger pieces to be locked into each other and the finer material serve as a kind of glue for dense filling between the bigger pieces.

It is necessary to have enough fine material, especially clay that fill the small interstices in the material and bind effectively together all the other fractions without excessive drying or shrinkage. Otherwise, too much clay will make the material too much flexible. Minimum percentage of combined clay and silt should be between 20%-25% and the maximum between 30%-35%. Similarly The minimum percentage of sand should be between 50%-55% while the maximum is between 70-75%. In conclusion, proposals tend to converge between a 30%-70% balance between clay/silt and sand proportions [1].

Soils with no voids can be achieved theoretically if their particles are completely spherical and follow the Fuller formula $p=100(d/D)^n$.

Where: p is the proportion of grains of a given diameter, d is the diameter of grains for a given value of p, D is the largest grain diameter and n is the grading coefficient.

If the grains are completely spherical n is equal to 0,5. Normally in construction n has a value between 0,2 and 0,25 [7].

Laboratory test

The more generally accepted laboratory tests used to obtain the particle size distribution of a soil sample follow the procedures set out in IS 2720, for civil engineering classification. The procedure comprises wet sieving, dry sieving and Hydrometer to establish fines grading [9]. First for the wet sieve analysis 200 gr of soil are passed through 75 µm sieve. The material retained on 75 µ sieve is then dry sieved Sieve analysis was done using a set of sieves 4.75 mm, 2 mm,1 mm, 600 µm, 425 µm,212 µm,150 µm and 75 µm. The material retained on each sieve was weighed along with that the empty weight of the sieves were also measured. Material passing through 75 µ sieve is then taken for hydrometer analysis. Hydrometer readings of 30 sec, 1 mint, 2 mint, 4 mint, 15 mint, 30 mint, 1 hr, 2 hrs and 24 hrs are recorded for the analysis. From the particle size distribution analysis , the quantity of different particles present in the soil sample is found out. PSD curve is plotted with particle size and percentage passing in x and y axis respectively of semi log graph.

Field test

The jar test is a field-test used to establish approximate (volume) proportions of the main soil constituents. In preparation the jar is quarter filled with the test soil and then filled with water and shaken vigorously. The jar is then left to stand for an hour and then is shaken again. The different soil elements precipitate at different rates and therefore after around eight hours the depth of each distinctive layer can be measured [10]. The test can provide a crude approximation of grading but its reliability is questionable with significant errors reported [7].

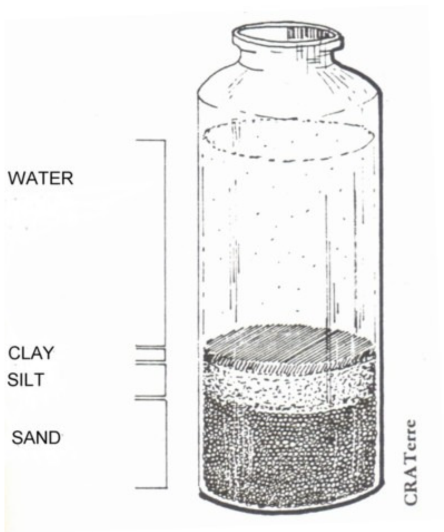

Figure 2.2: Jar test sedimentation [6]

The cohesion test (ribbon test) is also performed in the field. The loam sample should be just moist enough to be rolled into a thread 3 mm in diameter without breaking. From this thread, a ribbon approximately 6 mm in thickness and 20 mm wide is formed and held in the palm. The ribbon is then slid along the palm to overhang as much as possible until it breaks (see Figure 2.3). If the free length before breakage is more than 20 cm, then it has a high binding force, implying a clay content that is too high for building purposes. If the ribbon breaks after only a few centimetres, the mixture has too little clay. This test is inaccurate, and at the BRL it was known to have margins of errors of greater than 200% if the loam was not well kneaded and the thickness and width of the ribbon varied [11].

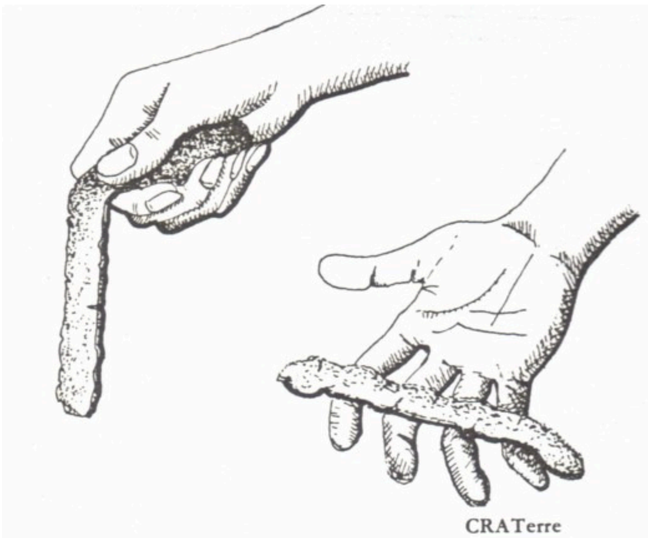

Figure 2.3: Performance of the ribbon test [6]

2.2.1.2. Determination of Atterberg limits – Consistency limits

Consistency or Atterberg's limits are the water content at which the soil changes its states to liquid, plastic and solid state. Determination of consistency limits is important for classifying the soil and to find the suitability for rammed earth construction. Atterberg limits includes liquid limit, plastic limit and shrinkage limit from which the plasticity index and shrinkage index can be found out.

The Solid limit, shrinkage limit and plastic limit.

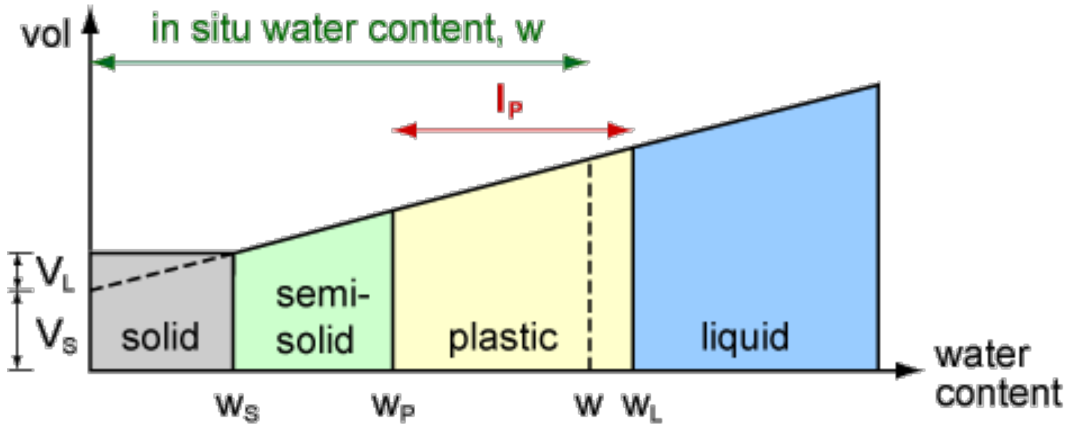

Figure 2.4: Graph representing the consistency limits relying upon the water content [12]

Solid limit – Shrinkage limit

Shrinkage limit reflects how the soil responds to moisture.

Shrinkage depends on the proportion and type of clay selected. Various clay types in pure form can shrink as little as 4% or as much as 25%. The most preferable clay minerals in rammed earth application are Kaoline and Illite [13].

The procedure for the calculation of the shrinkage limit based on IS 2720-6 [14]. 100 gr passing through 425 µm sieve are mixed with distillate water to get a paste. It is placed inside a shrinkage disk. Weights are measured before and after drying the paste inside the oven. Also the volume of the soil disc is calculated before and after drying using mercury and the equipement showed here bellow.

Figure 2.5: Shrinkage limit equipment [15]

The shrinkage limit is to be calculated by using the formula:

$$\text{Shrinkage limit } (W_s) = W - \left(\frac{V - V_o}{W_0}\right) \times 100$$

Where W is the moisture content of the wet soil pat, W_o is the oven dry soil pat, V is the volume of the wet soil pat and V_o is the volume of the dry soil pat.

Plasticity – Plastic limit

Soil plasticity, the ability of a soil to undergo irreversible deformation while still resisting an increase in loading, is indicated by the plasticity index. The plasticity index is the water content increase (% of dry weight) required for a soil to pass from a plastic to a liquid state. Experimentally the plasticity index can be found by estimating the plastic and limits.

A standard method for measuring plastic limit is described in IS 2720-5 [16]. Soil is screened through a 425_m sieve and dried. On re-wetting soil is rolled out by hand on a flat surface, usually glass. The plastic limit is defined as the moisture content at which the soil can no longer be rolled to 3mm diameter thread without breaking.

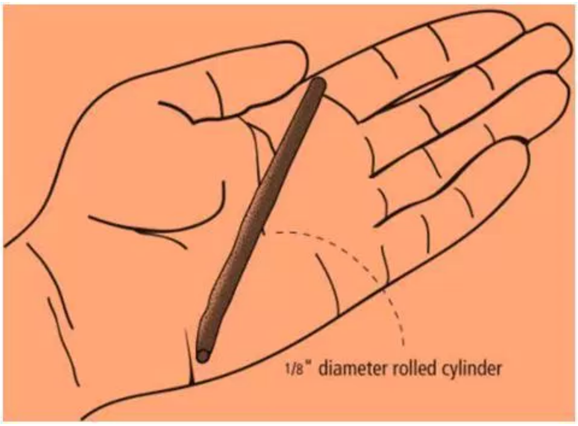

Figure 2.6: Methodology for plastic limit determination [17]

The plastic limit is to be calculated by calculating the water content of the sample:

$$\text{Plastic limit } (W_p) = \frac{W_{wet} - W_{dry}}{W_{dry}}$$

Plastic limit for unstabilized soils should be between 10% and 25% (12%-22% preferred) [18].

Liquid limit

The most common way to calculate the liquid limit is using the Casagrande Apparatus [16]. A soil sample passing 425 µm sieve is mixed with distillate water to get a paste. Then the paste is spread in the Casagrande apparatus with a thickness of 1mm and a standard grove is created in the middle of the paste. Then the number of strokes required to close the grove for about 12 mm is recorded. The test is repeated with different moisture contents at least 3 times for blows between 10 and 40. The liquid limit is obtained from the semi-logarithmic graph representing water content in arithmetic scale and number of drops in logarithmic scale, corresponding to the moisture content of 25 blows.

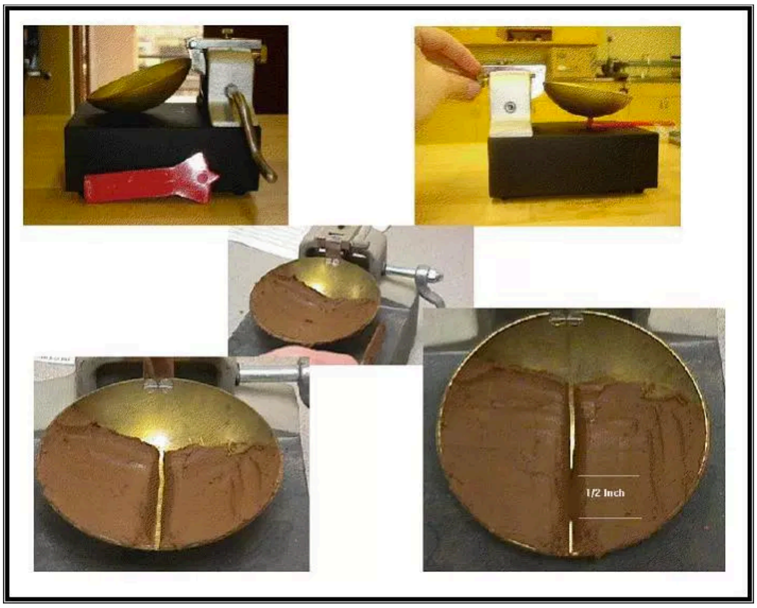

Figure 2.7: Casagrande apparatus procedure [19]

The liquid limit for unstabilized soils should be between 25% and 50% (30%-35% preferred) [18].

Plasticity index is also an important is the numerical difference between liquid and plastic limits. The plasticity index is an indication of the clay content and characteristics of the soil. The higher plasticity index is indicative of higher clay content and/or active clay mineral and that higher shrinkage will occur when the earth dries. For rammed earth, Alley (1948) proposed a Plasticity Index as low as 6%, however more recent research allows for higher values [18].

2.2.1.3. Maximum Dry Density and Optimum Water Content

The dry density of soil in rammed earth applications is dependant on soil type, the moisture content during compaction and compactive effort. Knowledge of the dry density of rammed earth is important during design to calculate loads on structural elements. A broad range of dry density values are quoted for rammed earth, varying from 1700 kg/m3 to 2200 kg/m^3 [1], [18], and the moisture content varies from 8 to 14% [7],[20].

Laboratory test

In laboratories, the standard ASTMD698-91 (1995) and modified ASTM D 1557-91 (1995) Proctor compaction tests are most commonly used to determine the compaction characteristics for proper control over the field compaction [21]. In India the method used is the same proctor as described in IS2720-7 [22].s

Mini Compation Test is used to determine the maximum dry density of the soil (MDD = γ_d) and the Optimum Water Content (OWC), as earthen material is very sensitive to water that affects its density. A small variation in density can produce a significant difference in strength.

The optimum moisture content (OMC) for rammed earth soils is critical in order to achieve maximum dry density (MDD) through dynamic compaction, which is related to the strength and durability of the material. If too little water is present, the soil will not achieve the same level of compaction due to the greater friction degree between particles. If too much water is present, the excess of water will fill the soil pore spaces, reducing the level of compaction and increasing the porosity when dried.

Procedure for Mini Compaction Test needs 200 gr of dry soil. Then 3% in mass of distillate water is added and increased in 3% for each new sample and mixed properly. The soil is compacted in three layers, applying 36 blows per layer using the hammer weight. To calculate a graph needs to be plotted representing the water content in the horizontal axis and the dry density in the vertical axis. The OMC and MDD correspond at the maximum point in the curve.

Figure 2.8: Mini Compaction test laboratory equipment

Field test

A good first approximation of the optimum moisture content can be achieved using the "drop test". A ball of moist soil, approximately 40 mm diameter, is compacted by hand. When prepared the soil ball is dropped onto a hard flat surface from a height of approximately 1.5m. When the soil is too dry the ball breaks into many pieces. When enough water has been added so that the ball breaks into only a few pieces, the soil is very close to its optimum moisture content. If the ball remains in one piece then the soil is too wet. The test is a reliable means of controlling soil moisture content during construction. For rammed earth, the soil is normally quite dry compared with other earthen techniques such as cob and adobe [6].

Figure 2.9: Drop test ball [6]

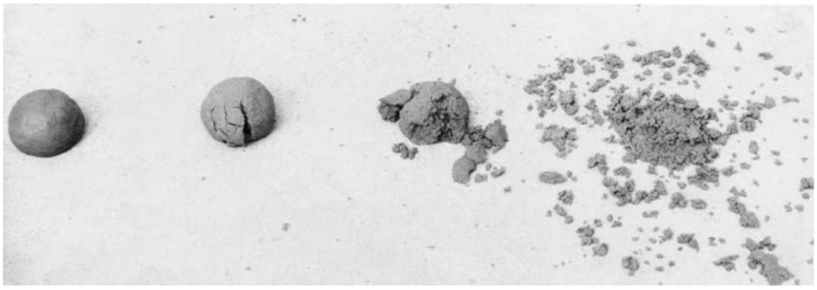

Figure 2.10: Drop test results depending on moisture content [11]

2.2.1.4. Unconfined Compressive Strength – UC Test

Compressive strength represents a basic quality control measure for rammed earth [2]. For this control we should put the samples off rammed earth into a compression testing device. They are then loaded in uniform uniaxial compression until failure.

Unconfined compressive strengths were calculated from the sample failure load using the formula:

$$\sigma_c = \frac{P}{A}$$

Where: σ_c is the compressive strength, P is the maximum applied load and A is the loaded surface area. It is assumed that the surface area does not change during testing and that the material behaves elastically [11], so that calculated value is the unconfined compressive strength.

The test for finding the Maximum Compressive Strength follows the IS 2720-10 [23]. A specimen is extruded using the tube sampler. Its mass is recorded and then it is placed in the compression device. Load is applied and its value is read for every 50 divisions of deformation on the dial. Keep applying the load until decreases significantly, the deformation passes the 15% or a failure is produced. The water content of the sample must be determined.

Figure 2.11: Laboratory equipement to mesure the UCS

Then the curve of Axial Stress versus Axial strain is obtained using the Strain (e) = $\Delta L / L_0$, corrected área $A' = A_0 / (1\text{-}e)$ and computing the specimen stress $s_c = P/A'$.

2.3.Stabilized Rammed Earth Construction

The use of stabilizers such as cement has derived out of a need to improve wet strength and durability in very exposed walls [18]. They provide also waterproof qualities and keep the soil from shrinking and sweeling [24]. However, in Australia and USA, cement stabilisation has become accepted routine practice in rammed earth construction irrespective of application [7].

To optimize the application of stabilization, the soil should meet different requirements. Organic matters must be avoided for the same reasons as for Natural RE, but also because of the interference with action of stabilizers such as cement [7]. Furthermore, mostly sandy soils and clayey soils are the most suitable for Stabilized Rammed Earth.

The main binders used for RE Stabilisation are Portland cement, lime, bitumen, natural fiber, fly ash and chemical solutions such as silicates [18], [24], [25].

2.3.1. Cement Stabilization

Portland cement is the most common stabilizing agent used. There are many advantages while using it. A cement gel matrix is formed; it brings together the soil particles and the bonding of the surface-active particles, like clay, within the soil [7]. It means that the compressive strength can be increased up to 18 MPa, a value not far from the 25 MPa for concrete [26]. This type of stabilization also improves the surface coat and prevents the erosion, as well as it improves the resistance to frost attack.

Conversely, there are some limitations and disadvantages using cement. Cement acts as a stabiliser against water, especially in soils with low clay content. The higher the clay content, the more cement is needed to produce the same stabilising effect. This means Sandy soils are more suitable for this type of stabilization [11]. Cement needs water to get hard. Since it gains most of its hardness or strength in days, moist is needed to keep this long. One way to do this is to put a watertight cover over the blocks or walls. Cement also reduces the permeability of the surface, the natural capacity to let the moisture passage through the soil.

The stabilization is done by adding a small content of cement between 3% and 15%. However, the average is in 6% and the economical maximum is in 8%.

2.3.2. Lime Stabilization

Slaked or non slaked lime creates a binder while reacting with the clay, which makes it one of the best stabilizers for this type of soil. Furthermore, it can be used with nearly all the soils having a plastic index greater than 12 [27]. Usually slaked lime is used because of safety, and it makes soils less sticky but not always increases the strength. Lime is not expensive as cement and you can get it nearly in any place in the world.

Soils for lime stabilization should have a liquid limit between 25% and 40% and it is ideally used for expansive soils [24]. Lime stabilized soils have a bulk density around 2,2 g/cm^3 [18]. For clay sand or clayey soils, lime stabilization is just as effective as cement or more.

The dosages are between 6% and 12%, and increases as the clay content increase. These soils will achieve its maximum strength about 6 times slower than a soil-cement.

Combination of Lime and Cement for stabilization its also a good idea. Lime will make the soil more reactive to cement, make it water proof or even more strong [27].

2.3.3. Fiber stabilization

Natural fibers can be used for stabilization, such as Wood, sisal, bamboo, Straw and timber. They are mostly used to increase the bending and tensing strength and thermal performance, but the shrinkage and the risk of cracks can be also reduced. According to Australian Standards, the ideal soil for fibber stabilization should have a plasticity index between 15% and 35% with the liquid limit from 30% to 50% [24].

Despite straw has been used with adobe blocks, it doesn't react with the soil in any manner, it will only make it weak and let the water get out easier during curing period.

2.3.4. Fly ash stabilization

Fly ash is the fine dust that is given off during the burning of coal, coke, lignite. and some other solid fuels, so it can be sometimes easily available. The lime and fly. Ash together with lime, make a cement almost as good as portland cement. It can be used on both sandy and clayey soils. When using together it is advised to use 2 to 4 times more fly ash than lime [27].

2.3.5. Bitumen stabilization

Bitumen is effective and has been used since many years ago for loam with low clay content. Normally 3% to 6% of this material diluted in water or a naphta is sufficient to stabilize the soil. When the solvent gets evaporate, it will glue the particles of loam together.

2.3.6. Sodium silicate stabilization

Sometimes called water glass, it is used in sandy soils. It is used in proportion of 5% in dry to increase the compressive strength [24]. Sometimes it is also used to create a thin “skin” of hard outsite of stabilized rammed earth blocks [27]

2.4. Recommended Soils and Stabilizers treatments

The soil selection scheme involves relating UCS criterion success rates to values of natural soil properties in order to discriminate between soils that are favourable or unfavourable, respectively, for stabilization, in the study realized by Steve Burroughs 2010 [28]. The textures of the soil were separate in Gravel-Sand % (Big particles) and Clay-Silt % (Small particles) with all the material bigger tan 19 mm discarded. The variables for study were the soil properties and were used in series of trials with different stabilizers to determinate the most efficient discriminators. The samples passing the 2 MPa UCS were successful and those who not where discarded.

The first stage used the LS to discriminate three classes of soil. First class soils with LS >11 have 29 % of success in UCS criteria, second class soils with 6≤ LS ≤11 have 69 % of success and third class soils with LS <6 had 93% of success. The soils of the first class should be discarded.

The second stage of soil selection was discriminate for sand content. First category with sand content <64 % has a succession rate of 86%. Second category with sand content ≥56 % of sand has a succession rate of 56%, which makes them unfavorable for stabilization.

The third stage clay-silt content is used. First category with silt-clay content ≤20 % have a success of 89%. Second category with silt-clay content 21-35 % have a success of 100%. Third category with silt-clay content >35 % have a success of 80%. Although they all have an overall success high, third category soils lie on the margin of favorability for stabilization, in terms of achievable strength and shrinkage cracking during curing process.

The study realized can be resumed in the following scheme:

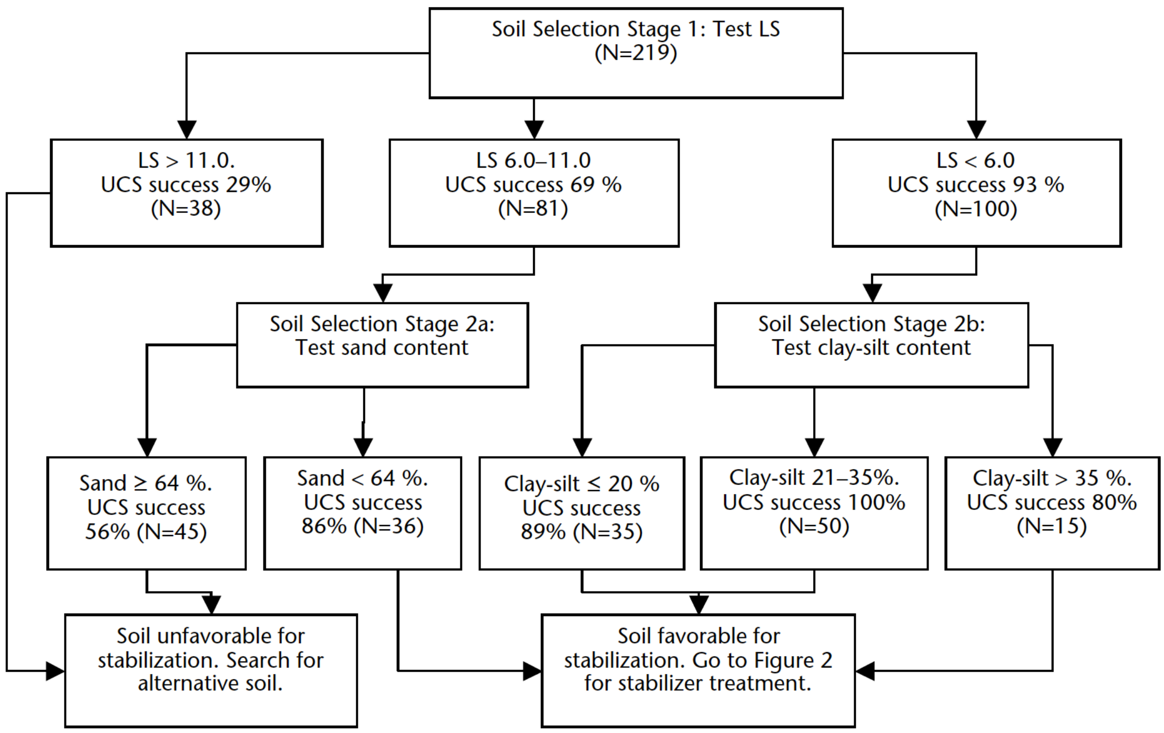

Figure 2.12: Determination method to determine the suitability of a soil for stabilization [28]

The LS is used as the first discriminator because the property reflects the textural characteristics of the soil and how it responds to moisture, both having an influence in the mechanical properties.

2.4.1. Cement and lime stabilization

The two best categories of soil are those with LS <6 and clay-silt≤ 20 % or with LS <6 and clay-silt 21-35 %, with succession rates of 89% and 100%.

The stabilizer treatments summaries and recommendations for soils deemed favourable for stabilization are described in the following scheme, reducing the time and effort spent on performing stabilization experiments:

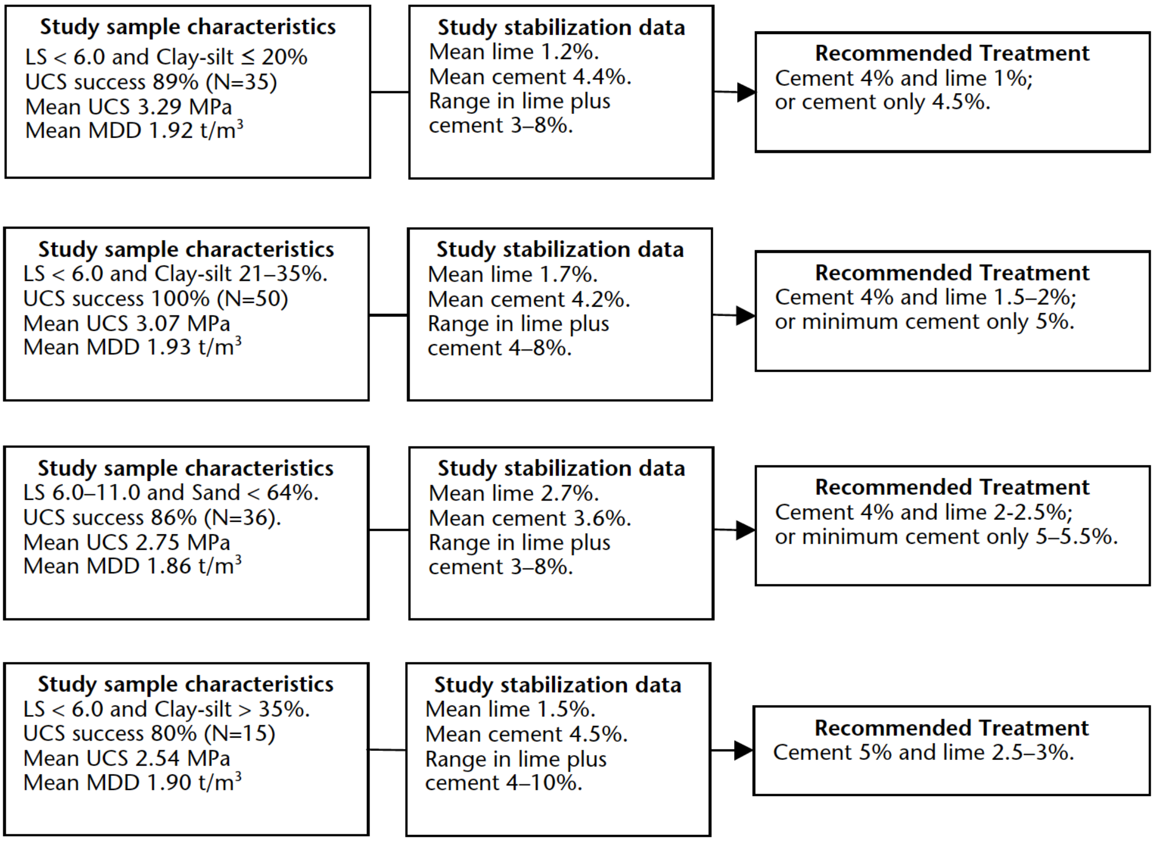

Figure 2.13: Best stabilizer treatment for every type of soil [28]

2.5. Mechanical performance

Mechanical strength of rammed earth is highly inconsistent, defined by various aspects of materials composition, construction technology, and exploitation.

Firstly, mechanical performance depends on properties and proportion of rammed earth components. It may differ in content and structure of its minerals (gravel, sand, silt and clay) and also in shape, from sharp cornered until smooth ones. Even small changes can affect RE performance.

Secondly, porosity has a straight relation to thus density. Also it is proved that each soil type has its own moisture content during the compaction.

Finally the component of strength of an earth mixture is achieved through matric suction that equals to difference between the pore air pressure and pore water pressure. It increases as soil dries, increasing the particle cohesion and thus strength [29].

When unstabilized, it works poor in tension but fair in compression. Laboratory tests of typical earth mixture (30% gravel, 45% sand, 13% silt, 12% clay, moisture content between 5-7.5%, dry density between 1700- 2100 kg/m3) indicate the ultimate compressive strength in range between 0.6 – 3.0 MPa [7]. Though considering the vast variety of decent mixtures the range can be broadened to 0.5-5 MPa [11].

For stabilized RE, compressive strength values can go from 9 to 14 MPa in wet state up to 15 to 19 MPa for dry state [13].

An simple test to have a first idea of the compressive mechanical performance, which is the most important in structures, is the UCC test. The primary purpose of the unconfined compression test is to quickly obtain a measure of compressive strength for those soils that possess sufficient cohesion to permit testing in the unconfined state. The procedure to follow is the IS 2720-10 [23].

2.6.Durability

Durability in the context of earth construction means the ability of the structure and all its elements to withstand the destructive action of weathering and other actions without degradation to the expected service life. Rain and frost are the most destructive natural actions causing erosion and deterioration of the earthen elements.

Durability of rammed earth is assessed by a variety of accelerated erosion tests, though there remains little correlative data between tests and field performance.

The most common is the weathering test, which is done by a spray as recommended IS: 1725-1982 [30], on cubes of 150 mm x 150 mm. According to the standards, the block to be tested is to be mounted on a test rig, such that only one face is exposed to a shower of 10 cm diameter with 36 holes of 2 mm diameter and discharged water should find an exit without wetting the other faces or getting collected such that blocks get immersed. The shower is placed at a distance of 18 cm from the block and is arranged by the side, such that the complete face gets exposed. The face of the block is exposed to a shower for 2 hours as shown in Figure 4.5 and then the exposed surfaces of the cubes are examined for possible pitting.

2.7. Thermal performance

The thermal performance of a material can be analysed through the Thermal Conductivity. It is the property of a material to conduct heat. Heat transfers occur at a lower rate in materials of low thermal conductivity. The IS units for Thermal conductivity are [W/(m·K)].

For URE Thermal Conductivity (k) is typically in a range between 0,5-1,2 W/m·K [11].

In the absence of Laboratory test data, the thermal resistivity (R) of an SRE wall can be calculated using the formula:

$R = 2{,}04d + 0{,}12$ [m·K/W]

Where d is the cross-sectional thickness of the wall element in meters.

As thermal resistivity is the inverse of thermal conductivity, this equals to an optimistic thermal conductivity of 0,46 W/m·K and means that RE is better insulator than concrete and brick[31].

Concrete with a density of 2240 kg/m3 have a thermal conductivity of 1.3 W/m/K or more depending on the quartz or quartzite sand content. This means rammed earth can contain or absorb more heat than concrete does even though it is less dense [32].

RE when used as external walls provide a long lag thermal long time lag. As a result, the internal temperature in summer will be likely to be lower than the outside during the day and the peak of the internal temperature will occur several hours after the peak outside.

Another important term to consider is the thermal mass, described in 2.1.2. Thermal mass is related to thermal conductivity but also to the specific heat of the material. The specific heat (Cp) is the energy (J) necessary to increase the mass of 1Kg of the material 1K. The specific heat of RE is between 1290 KJ/Kg·K and 1830 KJ/Kg·K.

The capacity of the material to transmit the temperature will depend upon on the thickness of the wall, which will affect the different coefficients of thermal performance of materials.

2.8. The process of RE

Rammed earth process depends and has to be adapted to many factors:

- Weather: It is not possible to proceed if the temperatures are low as in winter season because its effect on curing. Neither is possible during the monsoon season because of the possible increase of water content of the mixture.
- Quality of the soil available
- Dependability of tools
- Availability and generosity of the coworkers: Heavy and effortful process

The project can be experienced as a kind of meditation: the quality and misery of a lose soil who can be transformed into walls. It is a heavy an effortful project who when is well organized and planned becomes easy.

During the process many small problems appear regularly on the run.

It’s because of those problems and unpredictable factors involving technical, material, contractual, social, psychological aspects that it needs an organization of the whole process:

- Methodical approach
- Implementation of adequate tools: reduces physical effort and peoples energy
- Regular cleaning of the place
- Flexibility of organization
- Capacity of quick trouble shooting
- The role of an overseer (hidden eye) is fundamental
- Commitment of all the workers is essential
- Harmony of the team: Makes the work more enjoyable. Prepare other ludic activities.
- Generosity in providing good food to the workers

The help of a contractor can be useful when the experience in building with RE is too low but cannot avoid to be expensive, because his knowledge, machines and time has to be payed. It can be also avoidable depending on the own capability to develop, competence and involvement. However, it is recommended to make use of them during the early stages when they can generate deep changes and reorganizations and be independent when they became too expensive for what they provide to the project.

The process of performing rammed earthwork usually consists of fifth main phases: site preparation, soil preparation, formwork, compaction and post processing.

2.8.1. Site preparation

2.8.1.1. Site selection

The first question to solve is Where to build?, choice of the site. The choice for rammed earth has only a sense if the soil is taken locally, on the building site itself or nearby. If it is not suitable, some complementary soil (for instance clay if it is too sandy, or sand if it is too clayey) has to be brought in, and the more transport is involved. Then the more it defies the main purposes of using rammed earth, which are being ecologically viable, low cost in terms of materials and in harmony with nature.

Then the land has to be examined, because it has to have good drainage. Standing water or muddy ground can be very destructive to earth houses. It water stands on the area after heavy rains, the lot will not be satisfactory unless trenches or ditches can be dug to carry water away rapidly. This specially effects when foundations are build also with RE technique and the walls are at the floor level, but can be corrected using other kind of foundations and using a first layer of concrete before the construction of the walls.

2.8.1.2. Suitability of soil

The next step will be to analyze of the suitability of soil as described in 2.2.1. Depending on the availability or not of laboratories for soil testing, they can be done in a more approximate way using the soil tests proposed for the field.

2.8.1.3. Foundations

The foundation is that part of the house that is built below the ground surface and supports the house. A properly built foundation will keep the house from being damaged or twisted out of shape due to settlement of the earth, high winds or frost action.

Different types of foundations exist; ones with different pierces or footings are used for different house construction techniques. For RE walls, continuous footings are the most commonly used.

The technique used for foundation differs depending on the type of construction desired, the thickness of the walls and the number of floors. In India three main types of foundation are the most commonly used:

- **Concrete foundation:** The one who is used for modern buildings. It is expensive and non Ecologicaly responsible but it assures a good strength for any type of building. Otherwise, poured concrete it is the most suitable, but probably the most expensive foundation.
- **Stones and concrete:** It is another common technique used nowadays. Avoid an excessive consumption of concrete as it is used only to fix the stones and provides a good strength.
- **Stones and mud:** This is the technique traditionally used in the village of Dewgain. Both stones and mud are available in Dewgains village and villagers have a lot of experience building with this type of technique.
- **Rammed earth:** Rammed earth has been used as a foundation technique since many years ago. It can be used if it is a zone where the water will not be sinked and not get stoked.

The choice of the type of foundation depends on the type of sous-soil, the type of building to be constructed and the materials available in the site.

The depth of the footings will depend on the climate. For freezing weather, foundations will go as deep as frost can ever go. For warmer climates the footings need to external deep enough to reach good solid free from vegetation. Deep averages usually from 30 to 45 cm. Exceptions can occur for soils with considerable swelling and shrinking, then depth will be enough to not experience a lot of seasonal moisture changes in it [27].

The size of footings will depend upon the strength of the soil and the weight of the house. To be sure about the value of the soil, a load test should be applying. However, as a general rule, shallow clays and silts should not be loaded above than 10.000 Kg per square meter. Gravelly and sandy soils should not carry more than 30.000 Kg per square meter.

The foundation walls, which sit on the footings and support the walls of the house, must be strong, have a flat surface to start the earth wall on, be straight and they must be leveled.

While considering the size, two things must be considered, the thickness of the Wall and the height of the RE Wall. They should be as thick as the walls and thicker if they have to support overloads such as interior floors.

The height of the foundation walls, meaning the depth, should be sufficient so that rain splash will not reach the RE walls and cause erosion. Depends on the amount of rainfall and the width of roof overhang.

2.8.2. Soil preparation

Once we have the source of soil, the next step is to plan carefully how to treat it for further phases. Main considerations are that several tones of soil will be displaced, an available source of water is necessary and soil mix must be prepared.

2.8.2.1. Digging process

It matters because of the money and time spent, they way the soil will be dug and moved to the placed it will be used. It can be done by men with picks and shovels or by an excavator depending on time limitations and budgets. However there are some points to have in mind regarding this process. Usually the deep soil will be in form of lumps. They must be broken up before the next steps. Also get rid of undesirable material such as roots, leaves, trash and other organic materials is fundamental for a proper further compaction.

2.8.2.2. Sieving process

According to [1] any material coarser than 5-10 mm should be sieved out. It makes the mixing process with the stabilizer easier and more effective.

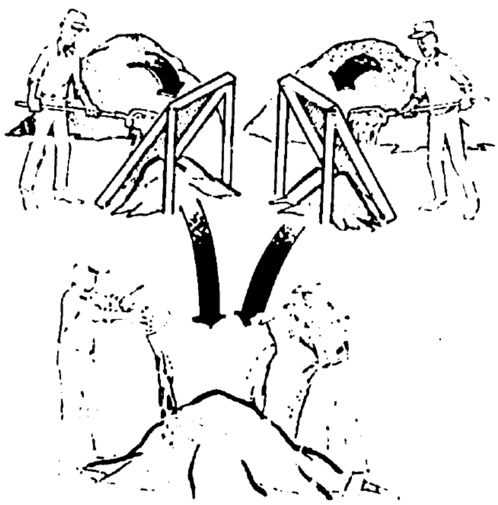

Table 2.3: Sieving process for RE [27]

2.8.2.3. Mixing process

First the moisture content of the soil recently dig must be analyzed, because it can be very close to the right moisture for better compaction. If a laboratory is not available, the experience of a RE builder will help to determinate how moist the soil should be, using the techniques described in *2.2.1.3. Maximum Dry Density and Optimum Water Content*.

Mixing is one of the most important operations in the whole process. The quality of a finished wall depends on good mixing of soil and stabilizer as well as with the water.

Different options are proposed:

- A motor powered machine. Examples used are motored-cultivator, cement mixer or more advanced and specific for soil such as Auramix 5000 [33]. However, cement mixers where rotation of paddles and drum rotate as one piece are only indicate for sandy soils. The best option is machines where teeth or paddles rotate inside a stationary drum or container.

Figure 2.14: Motored cultivator mixer [6]

Figure 2.15: Auramix 5000 soil mixer [33]

- A manual or animal powered mixer. Enterprises like Javo © offer manual powered mixing machines [34]. Other options are cultivation animal powered machiens.
- Manual mixing with board and shovels.

If available, a powered mixing machine can save a lot of time in a large project. Mixing machines should be purchased in accordance to the dimensions of the project so that their investing can be redeemed easily. Also homemade mechanically powered mixers can be build to reduce even more the money dependence.

For last, mixture with stabilizer and water should not be used later than two hours after its preparation, as cement will start its reaction with soil particles and the compaction will not be optimal.

2.8.3. Formwork

The formwork for RE construction is a temporary support used during soil compaction. It does not differ from concrete one, consisting of two parallel plaques or boards interconnected by spacers. It is probably the main challenge of the whole RE construction process, as it has to support the pressure of ramming, has to be big enough to avoid too many set ups and easy to handle, dismantle and settle up. Usually the time spent setting, aligning and striping the form is greater than the time spent transporting and compacting the earth [1].

Making the choice of formwork these criteria should be analyzed:

- ✓ **Strength:** the formwork should be able to withstand the outward pressure of the earth during compaction. Typically pressures during rammed earth compaction are considered to be much higher than general concrete Works, though area and period of time which pressure is applied is less [35].

- ✓ **Stiffness:** formwork should be sufficiently stiff to maintain the form without excessive distortion during compaction. Typically, forms should not deflect more than 3mm over the length between the ties under full pressure [24] or when applying a 150kg load at the mid-span between two supports [35].
- ✓ **Durability:** forms must be able to meet the expected number of uses under normal site handling conditions and appropriate maintenance, without performance deterioration.
- ✓ **Adaptability:** the formwork should be capable of accommodating variations in the width and layout of the wall to meet structural and architectural requirements.
- ✓ **Ease of handling:** formwork must not be too heavy or bulky in order to avoid making assembly difficult and time-consuming.
- ✓ **Ease of alignment:** formwork parts should include smooth horizontal and vertical slots, comfortable holes for bolts and smooth running ties to allow easy and consistent horizontal and vertical alignment.
- ✓ **Ease of compaction:** the shuttering system should not obstruct the compaction process.

Forms can be made up from metal, but wooden ones are preferred, as they will be lighter and cheaper in terms of building materials.

The designing and construction of the formwork is really flexible and adaptable at every project. The traditional ones are built using assembled horizontal wood boards with vertical thicker wood pieces and kept together using spacers and even ropes as shown in the following figure.

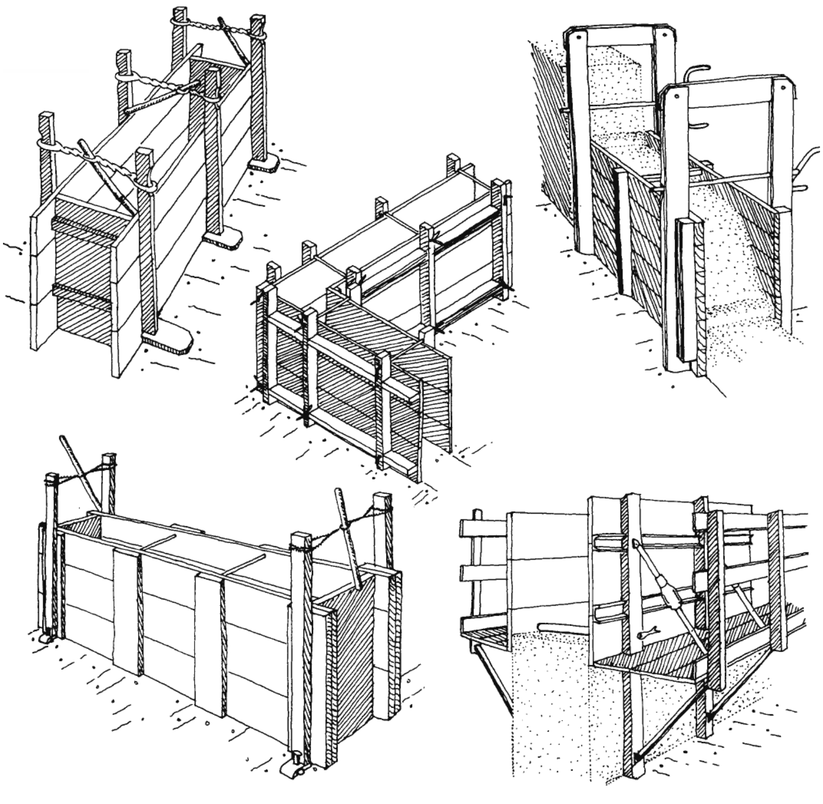

Figure 2.16: Traditional formwork [11]

The basic elements of any type of formwork system are:

- **Shutters:** The two big and continues boards with smooth surface that constitute the formwork. The traditional shutters made with plywood have a thickness of 20-45 cm [6], [11], [35]. Recommended size for shutters is 1,5-2,5 m of length for 0,6-1,2 m of height.
- **Stiff-ending or walers:** Shutters need to be stiffened by vertical or horizontal members so that they will not bend during ramming. Vertical stiffeners have a size of 5 cm thickness for 5-10 cm of width and they are positioned at approximately 75 cm intervals [11]. This distance can be increased to 100-125 cm by expanding the thickness of the shutter. If horizontal walers are used, they are placed at 25-30 cm intervals and go all along the shutter. They are made out of wood and the size of this walers is 5 cm thickness for 24 cm of width.
- **End stops:** The boards that close off the open sides of the formwork. They should have a minimum thickness of 5 cm and the height of the wall to build.

- **Spacers:** The bars that are used to set the width of the wall so maintain the space between the shutters. They pierce also the wall so that another formwork can be assembled at the top of the initial one. They cause openings to the wall that must be filled in after removal of the formwork. Metal bars or threads with a recommended diameter of 15-20 cm mainly constitute the traditional spacers, where nuts can be fixed. They vertical space between two spacers is some 25-30 cm and the horizontal is between 50-70 cm.
- **Wedges, ties and bolts:** They constitute the last and little adjusters for the formwork. They can be either direct through-bolts, cantilever bolts, threaded ties or ties with wedges [25].

Modern formworks using aluminum, Steel with supporting elements also with Steel and with minimal Steel through tiles have been developed during the last years. Small units formwork such as *Horizontally Sliding Crawler Formwork* or *Horizontally Sliding Crawler Formwork* have been developed by the Building Research Institute. These kinds of formwork suppose an economization of materials and an acceleration of the RE process thanks to the flexibility and easy assembling-disassembling. Other options are the integral formwork such as the *Australian Forming System,* the *California Forming System* or the *Continuous-wall system.* This systems developed in USA and Australia have produced very satisfying results and played a major role in the introduction of earth construction in market place [1]. Otherwise, they are very costly in terms of materials and non-ecologically responsible. Finally, corner formworks and even curved formworks contribute to avoid critical points in our structure.

Another important aspect is the cost. Economically and following the eco-responsibility talking, the best option would be a formwork manufactured with the materials locally available in the construction site.

2.8.4. Erection of the walls

The RE walls can easily be weight bearing, even for several levels if they are thick and stable enough. In some cases wooden weight bearings or concrete columns are chosen to support the weight of the structure.

As RE is a material that do not likes water, especially if it is unstabilized, a base for the walls can be created with bricks or concrete (see Figure 2.17, which will protect the structure in case of inundation [6].

Figure 2.17: Brick and concrete base for RE walls [6]

The walls have usually a thickness from 25 to 50 cm depending on the purpose desired. Insulated RE walls start at 40 cm thickness [11].

For the placement of the formwork, if we have created the base layer with the same thickness as the RE wall as in Figure 2.17 it will make the alienation easier.

Then the thickness of the layers has to be chosen. A good RE wall must be really well tamped specially in the bottom, then the layers must be thinner. Otherwise the possibility of collapsing will be higher and the bottom part will wash during rains. The thickness of the loose layer should be not less than 1 inch of the width of the tamping face. For example a layer of 4 inches can not be tamped with a rammer having a surface of 3x3 inches [27]. The ratio of compaction is approximately 0,38, meaning that a layer of loose soil having 4 inches should be compressed until 2,5 inches.

While tamping, with a pneumatic rammer we can ram the soil in one half or one third the time that would suppose for a manual rammer. Regardless of the quality of the soil, it will not be compressed enough if the moisture content is not correct neither if it is not tamped enough. For this reason the moisture content has to be checked often while mixing and also ramming.

The layer should be rammed continuously until the noise from the ramming tool changes from a dull thud to a clear ringing sound [27]. If it doesn't ring regardless the number of tampers, means something is wrong in the mix.

Making the windows and door openings can be done in two ways. The first one placing frames for them and ramming around. In this case we need to use solid supports to hold them or they will get out of place. The other way is to ram the earth first leaving an opening in the wall for the frames. In this case the end top of the formwork is removed and placed in the spot when the opening will come.

2.8.5. Protection treatments

Some treatments are applied to the surface of the walls and the structure to increase the protection or to make the walls look better, even if houses carefully compressed look better. Only sponging the surface with a moist felt towel just after dismantling the formwork will easily produce a smooth surface [11]. Also the best protection for the wall is a generous roof eaves.

2.8.5.1. Coatings

Stabilized RE walls can be let opened at air and it is not adviced to apply any sealer or coating. Otherwise unstabilized must be cover with mud, cement or lime plaster [13]. Other options are a coating of paint or use a waterproofing sealer that allows the wall to breath and to transmit normally the moisture through the wall. The inner walls can be impregnate with a dust sealer if deemed necessary [6].

2.8.5.2. Sealing of the structure

From our visit to Auroville Earth Insitute©, they recommended to create a concrete belt connecting the top of the walls to distribute the load along the wall for the roofing construction

2.8.6. Roofing methods

Any of the common roofing methods used in ordinary houses can also be used in RE houses. The most commonly used are thatch or metal sheet roofs, as they are easy to install and cheap.

Considerations to have in mind in order to choose the roof are the same as for the choice of the walls:

- Strength capacity of the walls for the roof supporting
- Availability of resources
- Suitability with the weather
- Fireproof and waterproofing properties

One of the biggest challenges when building in developing countries is the roof, which represents 25-30 % of the total cost of the structure. To be in concordance with the rest of the structure, three types of earth roofs are proposed, as they will reduce the construction cost, are waterproof and suitable with the specified climate.

2.8.6.1. Bunker fill roof

It is a flat roof consisting in large beams, sometimes called vigas (US) who support a thick layer of compacted earth. These supports have a size of 15-20 cm of diameter and they are separate 76 cm apart. A second layer is necessary to cover the beams to support the earth filling. This can be composed of lumber or a bamboo net structure. The top should be made like the RE walls, with a minimum thickness of 10 cm. In case of abundant rainfall, a protective surfacing coat may be needed. The rain must not fall down the RE walls, so a canal drain system has to be created.

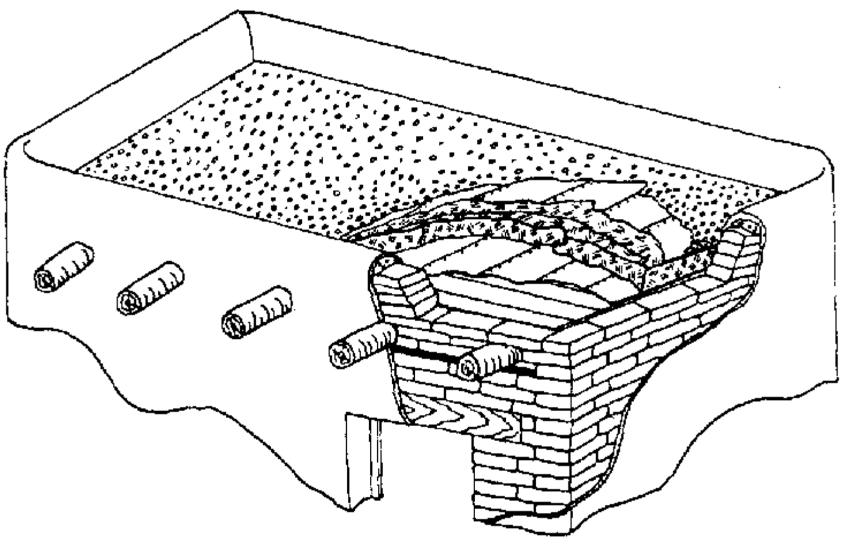

Figure 2.18: Bunker fill roof structure [27]

2.8.6.2. Arch of Vault roof

This kind of roofs are used in areas were wood is not available. They have been used for centuries, although they require good masonry skills.

These arched roofs are usually made with bricks, yet SREB can be used. A quick-setting type of mortar is required, such as gypsum. If cement or lime mortar is used, a form to support the brick until the mortar sets will be required, which will increase the inversion to build with this technique.

The vaults or domes exert a big load on the walls. Normally the walls supporting this type of roof are made very thick (60-90 cm). Otherwise, it depends on the design of the structure and repartition of the forces. A concrete bond belt around the top of the structure can make possible to reduce the thickness of the walls. However, a qualified civil engineer should design any such of walls and roof.

Figure 2.19: Auroville Earth Vault roof [3]

2.8.6.3. Earth tile roofs

Earth tiles have been always used to build roofs, specially in India. They can be made by pressing in a block-making machine, they can also be made with sun-dried adobe, or with clay and posterior sun-dry. Sun-dried tiles are made using also straw or grass, which prevents the erosion and increases the thermal insulation. The tiles are placed on a strong frame structure, that can be made using wooden beams and a bamboo sticks or wooden strips (stringers) creating a net or intertwined structure.

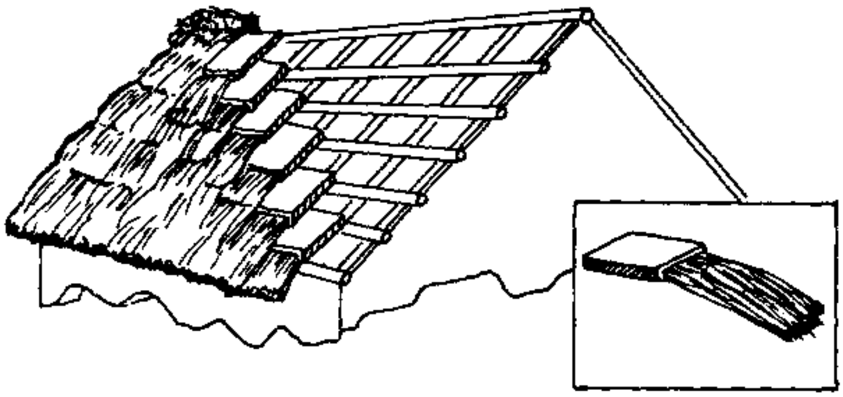

Figure 2.20: Structure of earth tile roofs [27]

2.8.6.4. Bamboo for roofing structure

Bamboo is a strong structural material that has been used forages in construction, because of its excellent strength properties. It is also really abundant in Asiatic countries such as India.

If it is properly treated its durability can be increased up to 20 years and can be a substitutive of Timber, especially for roof structures. It also protect the material against insects, especially thermites.

Here is presented the treatment technique learned during our visit to Bamboo Center® and Sacred Groves® community, both in Auroville.

To treat the bamboo a solution needs to be prepared, which implies the following components:

- 50 Kg of Boric Acid
- 75 Kg of Borax of Sodium Borate
- 7000 liters of water

To prepare the solution the two components must be mixed little by little in small amounts of water and then dropped into the big tank. Once all the components are mixed in water, the tank must be filled and mixed together to have a homogeneous mixture.

Then the bamboo needs to be drilled all the length of bamboo in order to let the water get inside of the "bamboo meat". Inside this solution 100 bamboo sticks can be soaked in the tank and must be soaked for at least 48 hours. The next step is to dry under the sun those sticks for 48 hours turning them regularly to avoid cracks because of the fast drying.

2.8.7. Flooring methods

The most desirable floors nowadays are wood floor, cement slab, cement tile or clay tile surfaced floor. However traditional floors made with adobe, lime or mud plastering and cow dung are demonstrated to be much healthier and naturally antibacterial. Here bellow, an alternative of this traditional methods is presented, by using rammed earth.

2.8.7.1. Rammed Earth floors

To make the floor with compressed earth, it is necessary to have a soil with the same characteristics that for the walls and follow the same steps than with walls, but is necessary to sieve the particles bigger than 4 mm as well as add a bigger percentage of lime or cement to stabilize to make it though and durable.

Two layers of 4 cm are desirable. The first can contain less percentage of stabilizers because it will not be in contact with external facts. The upper layer requires 2 to 5 times more stabilizer than the RE walls.

The inconvenient of this type of floors is that they must be cured by sprinkling water until its curing period desired.

2.8.8. Cost of Rammed earth construction worldwide

There are many factors influencing the rate of RE construction, such as the design, the productivity or the local context.

Productivity rate vary from $1m^3$/day to $3m^3$/day as it is a labor-intensive method of construction [7]. It means it is a cheaper alternative to concrete solutions in developing countries where wages are low, than in developed countries where mechanized materials are more available than labor force.

The materials cost depends on grand part to the soil resources available, varying form a perfectly suitable soil to a inefficient soil that needs form other fines to make it valid. Furthermore, the initial inversion in machinery and equipment will have a big impact depending on upon projects it is redeemed.

In Austalia for example, RE is really expensive since the labor costs are really high. One of the most famous architects in this domain, Luigi Rosselli estimates the price of square meter of double brick structure in 421 USD, 737 USD in RE, 789 USD in concrete and 947 USD in stone.

In UK, Rowland Keable, with a huge experience working with RE, estimates a huge difference between constructions. He considers an average price of 250 USD per square meter of RE structure in front of 790 USD for double-brick structures.

In Bangladesh, Simple action for the environment built rural homes with RE in 2011. It costed 3,66 USD per square meter, as the price with double brick would have been 6,67 USD [36].

2.8.9. Applications on real cases

The use of RE eradicates in the main principle of using available local materials. Recently, this technique has come back to light due to its relation to health wellbeing and its ecofriendly characteristics.

Rammed Earth first constructions date from 5000 BC, some of them discovered in Assyria and China. Actually, the 4000 years old Great Wall of China was originally built using RE (see Figure 2.21). Also the citadel of Bam in Iran dates of 2500 years old (Figure 2.22) [13].

Figure 2.21: Great Wall of China made with RE [37]

Figure 2.22: citadel of Bam in Iran [11]

In modern times the soil processing and the machinery and tools available are improved enormously, reducing the time for preparation, increasing the quality as well as precision while ramming and obtaining better consistency and aesthetic results. Some examples are presented here bellow.

Vineyard Residence at Mornington Peninsula, Victoria, Australia

Designed by John Wardle Architects, this 400 m^2 residence is situated in a large vineyard. The walls are built using RE angling outward and cross ventilation is achieved throughout areas [11].

Figure 2.23: Living room made with RE walls [11]

Figure 2.24: Inside view of the RE residence [11]

Figure 2.25: Inclined RE walls conforming the residence [11]

Youth Centre at Spandau, Berlin, Germany

The pedagogical facility in Berlin offers leisure activities and play for children and Young people. It is designed by Ask architects, Herman Sheidt and Frank Kasprusch. Its surface is

385 m^2. The massive RE Wall divides the building and serves to conserve the thermal energy and balances atmospheric humidity.

Figure 2.26: Outside view of the Youth center [11]

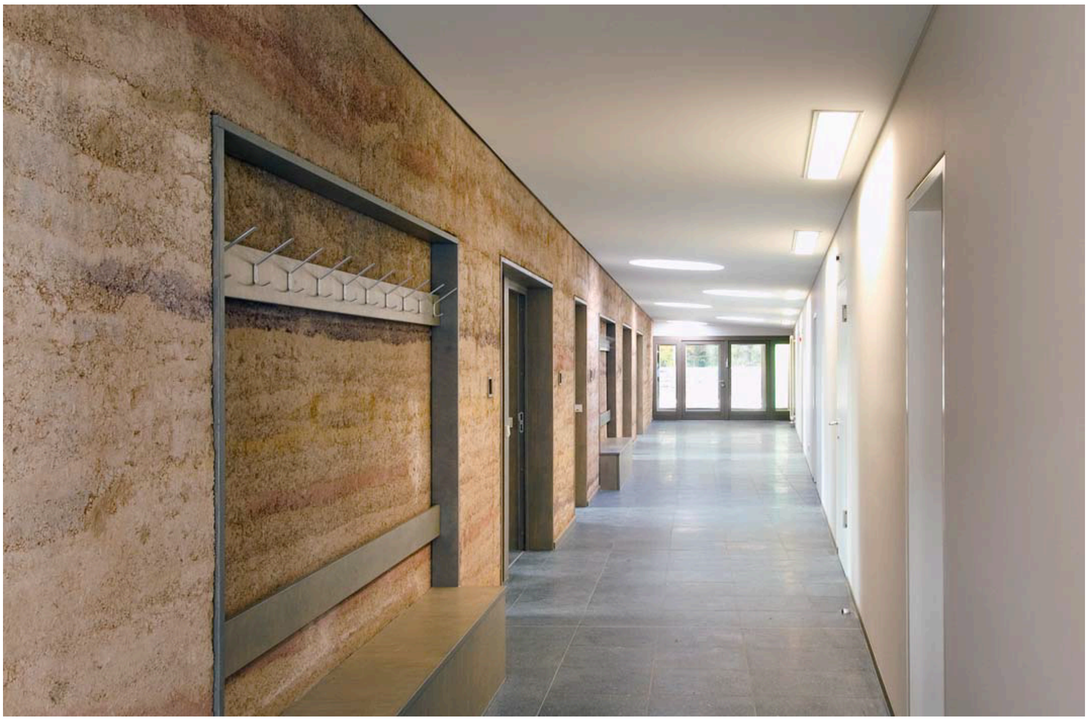

Figure 2.27: Thick RE wall dividing the Youth Center [11]

Center of Gravity Foundation Hall at Jemez Springs, New Mexico, USA

This 279 m^2 building designed by H.Predock and J.Frane in Santa Monica is used to primary teaching and as a meditation hall for existing Zen Buddhist compound. The thick RE walls serve to keeping the unwanted heating out during summer and warming at night.

Figure 2.28: Inner view of the Gravity foundation Hall [11]

Figure 2.29: Exterior perspective of the meditation hall [11]

3. Methods and field deployment

3.1. Fieldwork research

Housing issue is usually seen as a simple as the provision and installation enough houses for a people in a community with a fixed budget. This simplest vision is the reason of failure for projects that have been done in many rural villages in India.

Instead of that, an interaction fieldwork research specific for each community is necessary, which main 3 aspects should be studied in a first stage of the project:

- Identification of the housing needs and the number of houses to build or reconstruct
- Identification of the actual local techniques and materials available locally
- Identification of the particular social and environmental aspects of every zone

Truly and representative results for all the community under study, so a long-term sustainable solution can be achieved by a participatory approach win-win of the project team and the villagers. Participatory approach implicates engagement of all the social sectors, especially those who are more sidelined or excluded to involve them in the decision-making and managements of the resources, making them actors of its own development. It will also legitimate the solutions founded-out in a development-project.

The success in this participation approach means a methodological work, by using a checklist and a field journal to assist the informal process of taking data.

The purpose of this chapter is to present the community as well as to present the data obtained via survey checklist, which guide the process of a social community study based on the 3 main aspects.

3.1.1. Community under study

Devgain is a 418-hectare village, southeast of Ranchi. The nearest town is Tupudana, making the village part of the Namkum Block of Ranchi. It is separated into several geographic locations, which determine its primary communities. These features include a state highway in which the village developed along, and two rivers that run parallel to either side, the Siri and Bundubhera River, defining it's borders. Three main clusters emerged from this geography, where upper Dewgain is occupied by the Horros, the middle by the Hindus and the bottom by the Das family. These geographic locations also show the relations of religion and castes, where Hindus' and Christians are all found.

Figure 3.1: Indian map with the action state marked in red

Approximately 190 families reside in the village. The primary economy of the village is subsistence farming. This accounts for 90% of the labor force. The wealth of the farmers seemed to be polarized from one side of the village to the other. Some of the Christian families go to the city for work, therefore only growing for personal consumption. The Christian families seemed to have more education, and some conversed in English. However, most of the villagers had not completed primary school, nor were they interested in sending their children to further education. The village has a primary school for grades kindergarten through five, named St. Thomas Prathmik Vidhyalaya. It also provides a tuition program for young kids who are not at the age of homework yet, in order to watch them while parents are still working.

The community seems to work in harmony together. They have organized weekly meetings where important matters and challenges of the village are discussed. Sometimes there are petitions or proposals drafted, reviewed and sent to government bodies. The city has ample resources with several small stores along the main highway as it is shown in the following map.

Figure 3.2: Map of Dewgain village with main facilities

The identification of the 3 main aspects involves a list of questions such as:

- How the houses were built?
- Where do the materials for the house come from?
- How do the seasons affect the house?
- How do the climatic changes along the year affect the comfort of the inhabitants?
- Is there any maintenance that needs to be done in the house?
- By what the construction of new houses would benefit the most disadvantaged people in the community?
- How can a new construction method can be affordable for the most economic powerless people in the community?
- How a different type of construction will impact in villager’s perception?
- How can a different method of construction can improve environmentally and healthy the villagers live.

In order to better specify the different levels of detail, the following guide will be used for a correct identification and further implementation of a housing method system.

3.1.1.1. Identification of the actual constructing methods used for wall and roof construction

To make the study, the community was divided in 9 zones as per natural aggrupation of the existing houses:

Figure 3.3: Map of the village with 9 zones identified

The main purpose of the observation study was to identify the type of walls construction in every house, as well as the type of roof actually using and finally any observations as deterioration or any other useful data is reported.

Four types of walls construction were identified:

Traditional Mud construction

Mud is the oldest and widely used construction material. It is build using clay locally available mixed with water to obtain a paste. That paste is hand-compacted into walls of a big thickness around 35-45 cm. Then is sun-dried until obtaining this characteristic mud. Mud structures are ecofriendly, with a very low embodied energy, thus leading to sustainability [24]. This type of construction, as rammed earth, has a high thermal mass because also of its thick walls, which reduces the temperature fluctuations. Hence, they are indicated for arid regions with high fluctuations during the day or Semi-Arid regions with high fluctuation along the year. On the other hand this type of material has a low durability and resistance to erosion, which increases maintenance need. It also has no protection against insect attack, especially thermites. This kind of construction is predominant in the zone, especially for people economically powerless.

Figure 3.4: Traditional mud house in Dewgain village

Stone construction

Walls are constructed using dressed stones (manufactured stones shaped into construction suitable forms) and reconstituted concrete blocks. They are joined using mud traditionally but also concrete in houses with better finishes. This type of construction reduces also the temperature fluctuation because of its thermal mass. Differently of Mud construction, this one is more indicated for hot-Arid regions like Rajasthan [38]. This kind of construction is minor in Dewgain village.

Figure 3.5: Stone construction example in Dewgain village

Brick construction

This type of construction uses bricks called thermal or red because of its thermal properties or characteristic red color coming from its big clay content. They reduce the heat interaction between the indoors and outdoors, as the surface area to volume ratio is low. Brick structures are also high durable and strong. The method of construction is similar to stone construction, using mud or concrete to join the bricks piled together.

Figure 3.6: Brick construction house in Dewgain village

Prototypical concrete house

This houses are build using prefabricate metal molds and concrete, so they look all similar. Concrete is the less energy efficient, eco-friendly and cost effective technique. It is also not suitable for Dewgain Village, because of its high thermal conductivity compared to the rest of techniques.

Figure 3.7: Prototype concrete house in Dewgain village

For roofing construction 4 types of roofs were identified:

Traditional Clay Tile roof

This method for roofing construction is based on beams made of Sakhua wood, which is a long-durable and strong wood that was growing naturally in the Dewgain zone. Because of its uncontrolled exploitation it has currently disappeared. The next layer that covers the beams is a crisscross bamboo pattern, which at the same time is covered by grouped tiles. This traditional roof is a good thermal isolator method, but is neither waterproof nor fireproof.

Figure 3.8: Traditional clay tile construction in Dewgain village

Asbestos roof

Asbestos is a set of six natural minerals in fibrous forms. It is believed to be a good solution for roofing in some developing countries, while in 55 countries has ben banned and restricted in many others because its direct relation in causing mesothelioma and asbestosis. This two are caused by the inhalation of asbestos fibers suspended in the air. In addition, it has a high thermal conductivity, providing too much heat in the summer seasons.

Figure 3.9: Asbestos roof sheet used in Dewgain village

Concrete roof

Similar to concrete construction walls roof is build using molds to make thick roofs which impact event worst in the thermal comfort of the house since in hot seasons, when the position of the sun is high, it will impact immediately to the surface of the house heating the interior and making it impossible to live inside.

Figure 3.10: Thick concrete roof in Dewgain village

3.1.1.2. Survey

In regards to the survey, the goal was to get a broad understanding of the village housing situation at large. In order to do so survey guidelines were set up, which would guide into the selection of housing studies.

- Number of people in the house, age and occupations
- Wall construction type
- Flooring type
- Roofing type
- Materials used for construction
- Location of the Kitchen
- Number of bathrooms
- Number of bedrooms
- Common area, family space
- Desires for a new house

The survey was done in 15 houses including the different areas in which the houses are distributed in order to have global reliable results. The results can be

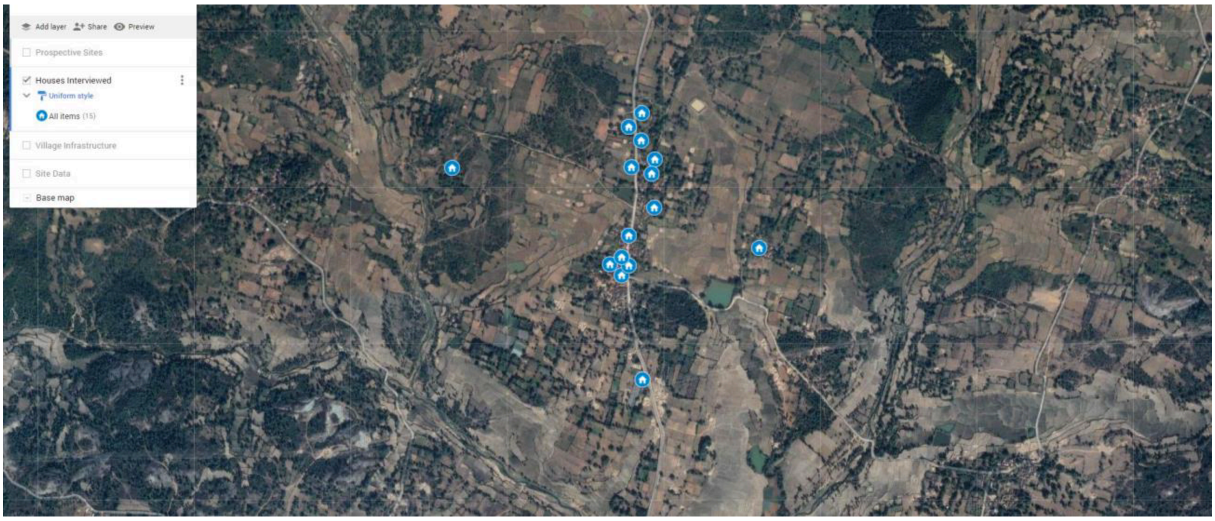

Figure 3.11: Location of the survey realized

As the results show in ANNEXURE A: SURVEY REALIZED IN DEWGAIN VILLAGE, the predominance is the Mud house with traditional roof and cow dung flooring.

It shows also that the main resources available are timber, bamboo and home manufactured clay tiles.

3.2.Problem characterization

The different visits to Dewgain village done by Amrita University members, in addition to the Amrita SERVE observations on the zone and even the villagers' claim have identified the lack of comfort and minimal facilities in the house as one of the major health and primary issues this community is facing.

Materials:

- Climate comfort during hot season, especially concrete houses but even in mud houses because the lack of electricity to use the fan.
- Leakage problems during monsoon seasons with traditional clay roof system
- Degradation of the wall structure, specially in mud houses
- Toxicity of asbestos roof. It can not be used as a roofing solution

Architecturally:

- Lack of openings for natural light
- No ventilation openings, especially in Kitchen. Really big issue that causes the intoxication of women
- Inexistance of toilets inside the house or attached to it

3.3.Solution design

The selected technique proposed to solve the issues that the actual houses are facing with is Rammed Technique. This chapter pretends to describe the previous work necessary to the application of this new technique in a territory where it has never been used.

In first instance, the implementation of RE in Dewgain village was planned throughout a community center design and construction. The purpose of this part of the project was multiple:

- First, provide a building that serves both the needs of visitors and villagers.
- Secondly, a real example of RE technique possibilities so that villagers could discover this new technique and experience its benefits by themselves.
- Thirdly, an example to introduce new architectural modifications to the existing buildings to solve the ventilation, lightning and distribution challenges.
- Finally, to teach the villagers about this technique and empower them to make them actors of their own development.

Based on architectural planning standpoint, the site recommended was the indicated in the Figure 3.12. Also because it is integrated into the residential fabric of the village, allowing a closer relationship between villagers and visitors.

Figure 3.12: Location of the construction site in Dewgain village

During the visit to Dewgain, 50 Kg of soil were extracted from the selected soil to proceed with de identification of the type of soil and its suitability or not for RE construction. To do so, the soil was extracted 1,5 meters below the ground level to assure the inexistence of organic matter as specified by all the manuals and handbooks [1], [7], [35].

The construction with RE is a big challenge for those not having any experience, even for those having a good theoretical knowledge about soil techniques in Civil Engineering. The construction skills can only be acquired by the own-self experience, mining a trial and error process.

Since the Ettimadai campus of Amrita University has at its disposable several resources for construction, a house prototype has been build in order to have a first idea of the possible challenges who can be found during the RE process. The daily issues can be analyzed an solved easily and fast in this milieu. Because of those reasons the construction of the community center has postponed as a further stage of the project after the construction of the Ettimadai Campus prototype.

The chapter is organized in main points. The first describes the initial process of soil analyzing, both for Dewgain and Ettimadai campus, so the soil properties can be compared. The second point is a summary of the tests realized in RE structure walls. Finally the third point is the application of the RE used to build a house prototype to have a real experience of the technique for constructing.

3.3.1. Analyze of site soil properties

Even if there is no provision or mention of RE in the building codes used in almost all around the world. The closest analogies that currently exist in determining the structural RE wall are the Concrete Building Code and the Masonry Building code. It is commonly referred to the design and engineering of SRE Walls. This approach has been supported by ASTM (Standard Guide for the Design of Earthen Wall Building Systems) [39].

The Bureau of Indian Standards (New Delhi) has also created a code for construction of Cement-Soil walls and primary a code for the identification of the soils for general purposes of engineering IS: 1498-1970 [40].

First of all, the in-situ soil of Dewgain has been analyzed to see its suitability for RE construction using the following tests. Also the soil of Coimbatore campus of Amrita University was tested for the prototype construction process.

3.3.1.1. Particle size distribution analysis

The procedure has been done as specified in IS 20720 and resumed in point 2.2.1.1, obtaining the following curves for the two different soils:

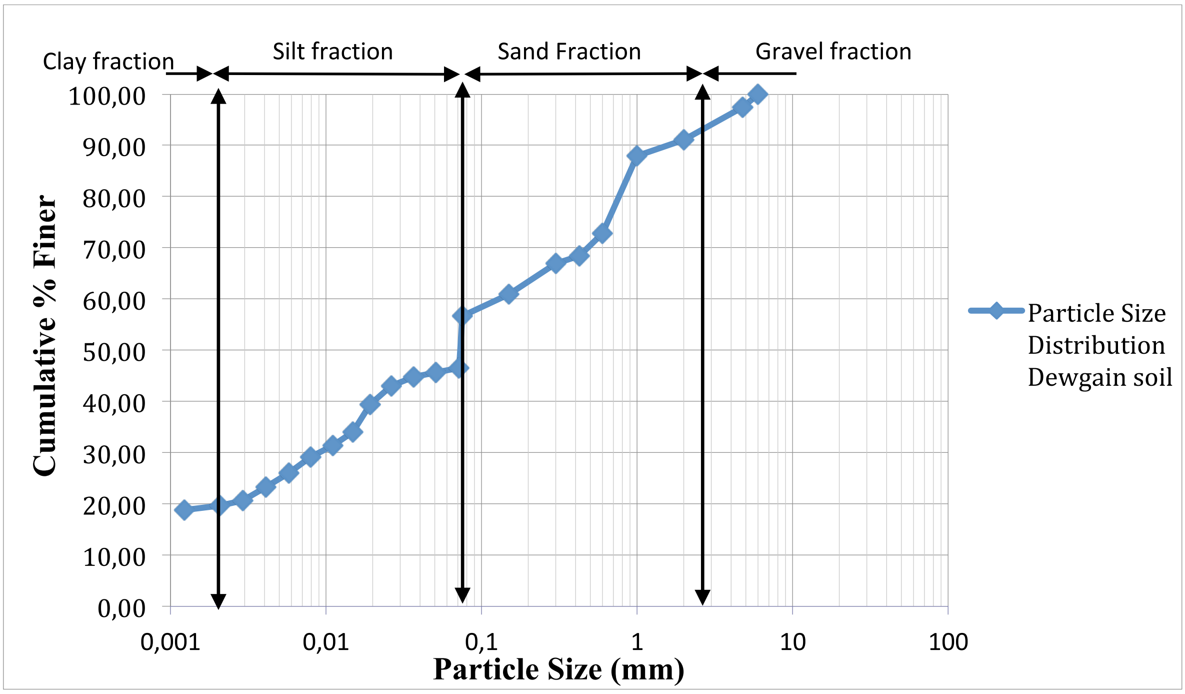

Figure 3.13: Particle size distribution graph for Dewgain soil

Particles	Gravel	Sand	Silk	Clay
Percentage (%)	8,95	34,37	36,96	19,72

Table 3.1: Percentages of fines in Dewgain soil

A soil suitable for cement stabilized rammed earth construction sand content should be greater than 50% and clay and silt content should be less than 30% [41]. The result obtained from the particle size distribution analysis of Dewgain soil shows that the soil is not suitable directly for cement stabilization [28].

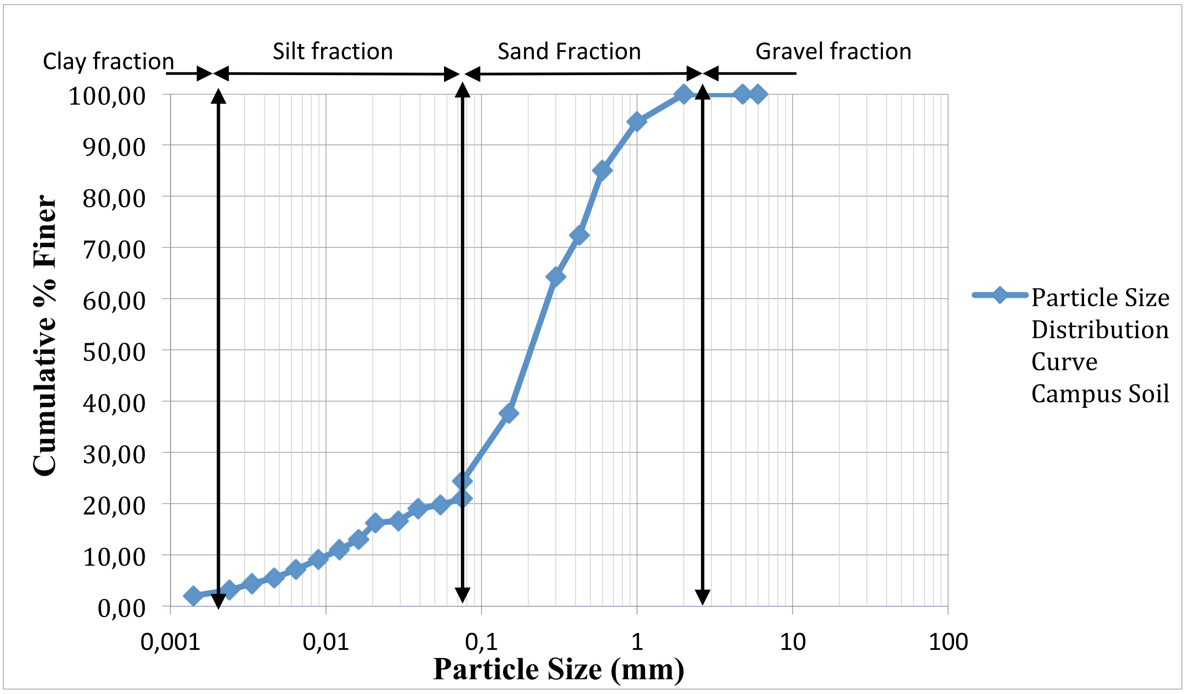

Figure 3.14: Particle size distribution for Campus soil

Particles	Gravel	Sand	Silk	Clay
Percentage (%)	0,00	75,58	21,26	3,17

Table 3.2: Percentages of fines in campus soil

On the other hand, Coimbatore campus soil is suitable for cement stabilization due to his high sand content and its clay-silt content between 21 and 35 % that makes the UCS success rate (strength superior to 2 MPA) of 100 % [28].

3.3.1.2. Consistency limits

The Consistency limits were calculated following the IS 2720 and as described in 2.2.1.2. Liquid limit was found out with Cassagrande's liquid limit apparatus, plastic limit by rolling the sample to form threads of 3 mm diameter and shrinkage limit using shrinkage apparatus. Liquid limit – plastic limit gives Plasticity Index (PI) and liquid limit – shrinkage limit gives shrinkage index. The limits obtained for the Dewgain soil as well as for Coimbatore campus soil under test are resumed in the following tables:

Dewgain soil consistency limits

Shrinkage Limit	Plastic Limit	Liquid Limit	Plasticity Index	Shrinkage Index
14,38%	21,88%	47,40%	25,52%	33,03%

Table 3.3: Consistency limits of Dewgain Soil

The plastic limit is in the preferred range 12-22 %. PI should be below 10-30% [7], as there should be proper consistency for the soil during the moulding. The reference also recommends a lower value for SI as it effects the shrinkage/swelling characteristics of the soil. The result shows that the soil is suited for RE construction even if it has a shrinkage limit high elevated.

Campus soil consistency limits

Shrinkage Limit	Plastic Limit	Liquid Limit	Plasticity Index	Shrinkage Index
18,44%	20,32%	22,47%	1,88%	4,03%

Table 3.4: Consistency limits of campus soil

The three limits are in the prefered ranges for natural RE[18]. Also the plasticity index is far below 6% and she Shrinkage Index is really reduces which indicates that effects of shrinkage/swelling are not predominant. From the consistency limits we can say that the soil is highly suitable for RE construction.

3.3.1.3. OMC and Dry density

The compressive strength and dry density of the soil depends on the compaction properties. Determination of OMC is required for the optimization of moisture for molding the rammed earth. Compaction test was done with standard proctor method in accordance with IS: 2720-1980 part 7 [22] and as descrived in 2.2.1.3. The different moulding moisture content is plotted against dry density for the two types of soil are plotted as showed in Figure 3.15 and Figure 3.16.

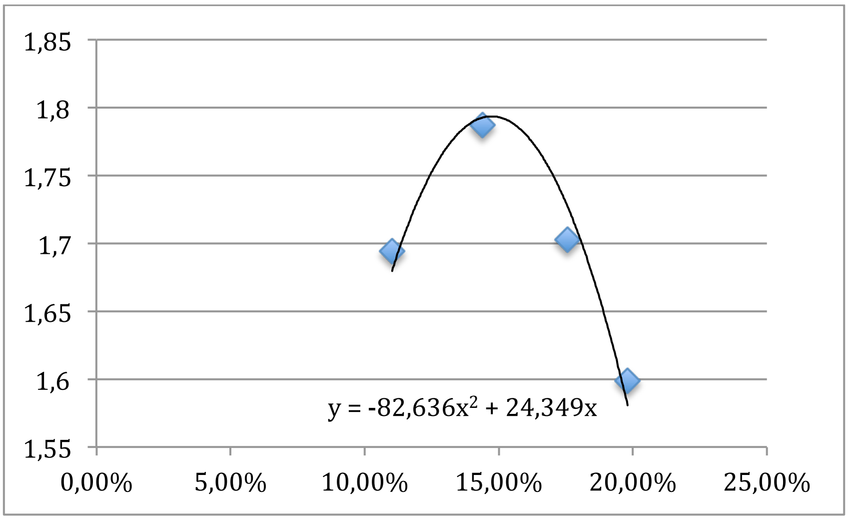

Figure 3.15: Mini Compaction graph for Dewgain soil

For the compaction curve obtained of Dewgain soil the OMC is 14,73 % and the MDD is 1,79 gr/cm^3. As the range of OMC is 8-14 % and the MDD between 1700 Kg/m^3 and 2400 Kg/m^3 for RE construction, we can affirm that the Dewgain soil satisfies OMC and MDD for RE further construction.

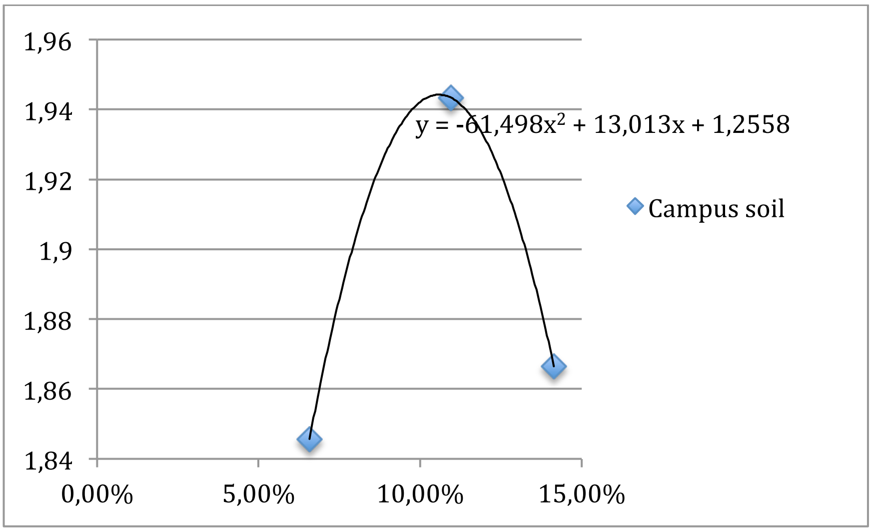

Figure 3.16: Mini-Compaction graph for Campus soil

From the compaction curve the OMC and MDD obtained respectively are 10,58 % and 1,93 Kg/cm^3. The reduction of OMC and increasing of the MDD respect the Dewgain soil reflects the higher content in bigger particles, which makes this soil more suitable for cement stabilization and also it will have better strength properties in natural state.

3.3.1.4. Unconfined Compressive strength

Firstly, the strength of the natural RE for the Dewgain soil was tested, in order to now in which maximum compressive strength we were starting form.

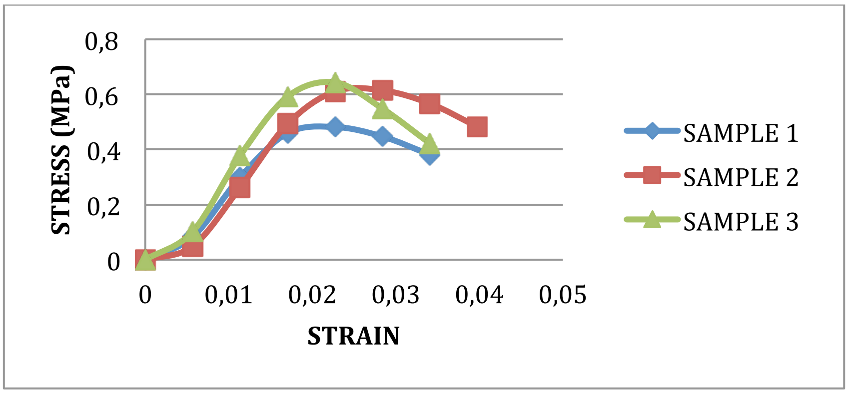

Figure 3.17: Graph Stress-Strain for Dewgain soil RE without stabilization

The medium maximum UCS for the three samples was 0,58 MPa.

3.3.2. Mixture and binder optimization

The chosen binder was cement as it was the material the more available and economic near the execution site.

Different proportions of soil, sand and cement were proposed according to the specifications of most appropriate soils for cement stabilization [28]. This was firstly done for Dewgain soil.

Compositions	1	2	3
Dewgain Soil	65%	62%	50%
Added Sand	30%	30%	44%
Cement	5%	8%	6%
Sand+Gravel	60%	57%	66%
Clay+Silt	35%	35%	28%

Table 3.5: Compositions of different Granulometry for different proportions with Dewgain soil

First of all the OMC and MDD for different contents of cement in Dewgain soil were analyzed, they are presented in the Figure 3.15.

Compositions	1	2	3
OMC	13,58%	12,61%	12,06%
MDD (gr/cm^3)	1,91	1,91	1,94

Table 3.6: OMC and MDD for the different proportions of mixture with binder for Dewgain soil

The selection of the cement content and added sand was made considering the UCS of a small sample test as shown in Figure 3.19 and specified in 2.2.1.4, for the Dewgain soil with the three compositions chosen:

Proportion	1	2	3
Cement content (%)	5	8	6
UCS (Mpa)	3,67	3,73	2,89

Figure 3.18: UCS for the different proportions with binder for Dewgain soil

Figure 3.19: Cylindrical samples used for initial UCS test

The UCS results show that by increasing the sand content from 60% to 66% the UCS decreases event if we are using more cement than in the proportion 1. As the principle of RE is using local soil, adding 30% of sand to the natural soil is enough to have a successful UCS.

Regarding the campus soil, only the OMC and the MDD has been analyzed with 8% of cement content, who has been chosen for the RE prototype. The respective values are 10,25 % and 1,93 gr/cm^3. There is a reduction of the water content event if the density remained the same.

3.3.3. Studies on stabilized rammed Earth Construction

After the identifications of the soil properties, different behaviors of RE are analyzed to have a first approach of his performance in real buildings construction. The principal characteristics to test are the strength performance, the resistance in front of erosion, its internal composition and its thermal performance.

3.3.3.1. Compressive strength test on prism specimens

The compressive strength in prism specimens is useful to predict the RE walls strength behavior. The compressive strength of masonry blocks needs to be done in prisms of height/thickness (h/t) ratio no more than 5 as specified in IS: 1905-1987 [42]. In this case, the prisms employed had a 450 mm height, 300 mm width and 150 mm thickness. The blocks have been compressed with layers of 9 cm as it can be appreciated in **¡Error! No se encuentra el origen de la referencia.**. Three different type of prisms have been tested, according to the necessities of the project:

1. First prism to be tested was build using the Dewgain soil with the composition having a better compromise between UCS and materials used. In this case it had 62 % of local Dewgain soil, 30 % of added Sand and 8 % of Portland cement.
2. Secondly, as the prototype was done using Ettimadai Campus soil, a second type of block was build using 92 % of soil and 8 % of Portland Cement.
3. Finally, during the construction of the house prototype of the campus a third class of prism was assembled to test. The calculation of soil, cement and water content has been done using approximate field methods and the mixture has been done using powered-mixers. The percentage of soil was approximately 7% and with a 10 % of WC. It has crucial importance to test these blocs done with the field soil in order to prove the correct procedure.

All the prisms have been cured for 28 days before being tested in the universal testing machine. The setup of the samples is as in **¡Error! No se encuentra el origen de la referencia.**. Two strain gauges were located in between layers as shown in between layers in the top level and bottom to measure the maximum vertical deformation.

Figure 3.20: Prsim compressed in 9 layers

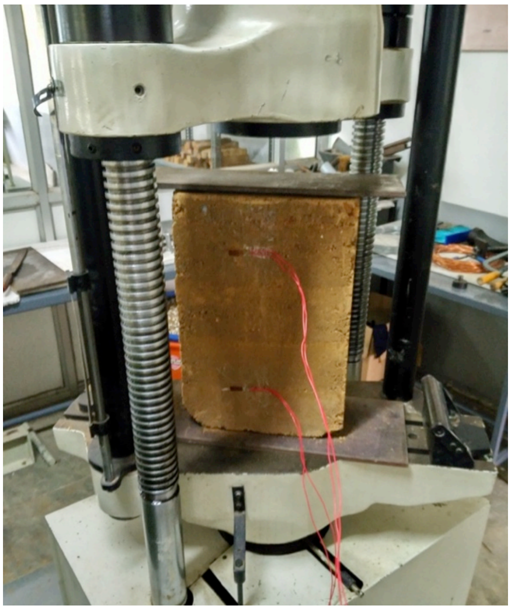

Figure 3.21: Setup of the sample in the universal machine

The load-deformation curves have been plotted for the three types of specimen:

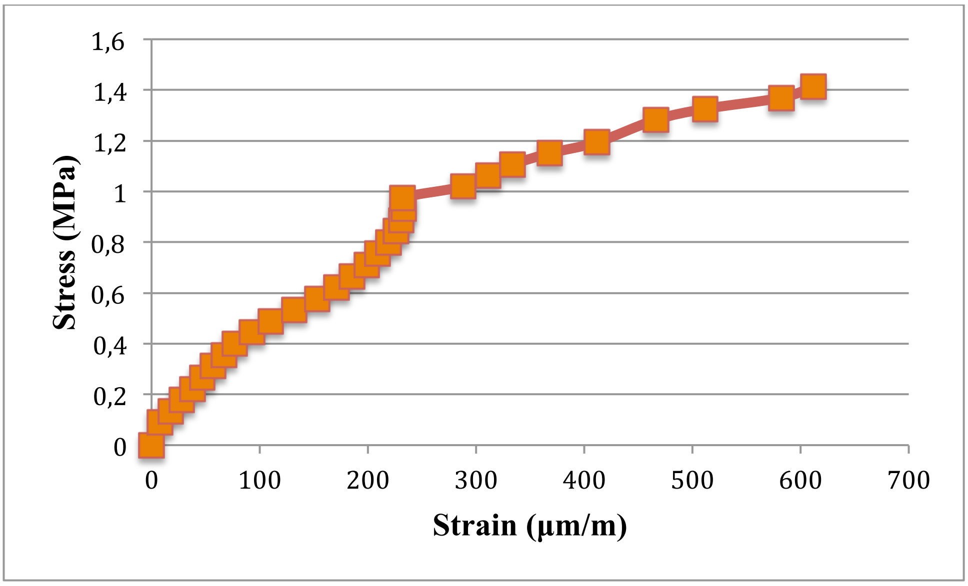

Figure 3.22 Stress strain curve of Dewgain soil

The UCS obtained for this sample was 1,41 MPa, far from the 2 MPa of minimum UCS. The sample failed without any line crack. It just failed by the particles discohesion. The factor of security of 4 is recommended by IS 1905-1987 [42]. Hence, the allowable compressive strength will be of 0,37 MPa. However, the value can be the result of a non-well compacted earth, as after 28 days of curing the soil was loosing and getting separated.

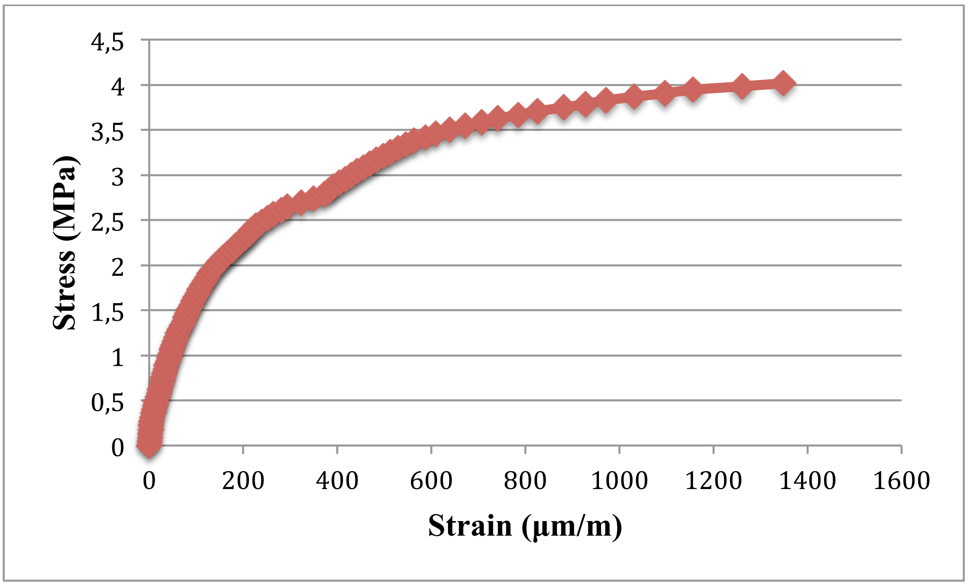

Figure 3.23 Stress strain curve of sample made in the lab from campus soil

The UCS for the sample created using campus soil in the lab was 4,02 MPa. The results show a big increase prior to the Dewgain sample, in which many factors can have an influence. The first of all is the different granularity compositions of the samples, this one having a high percentage of sand and being sieved until obtaining a fine soil. The second is a better compaction detected visually after the curing period.

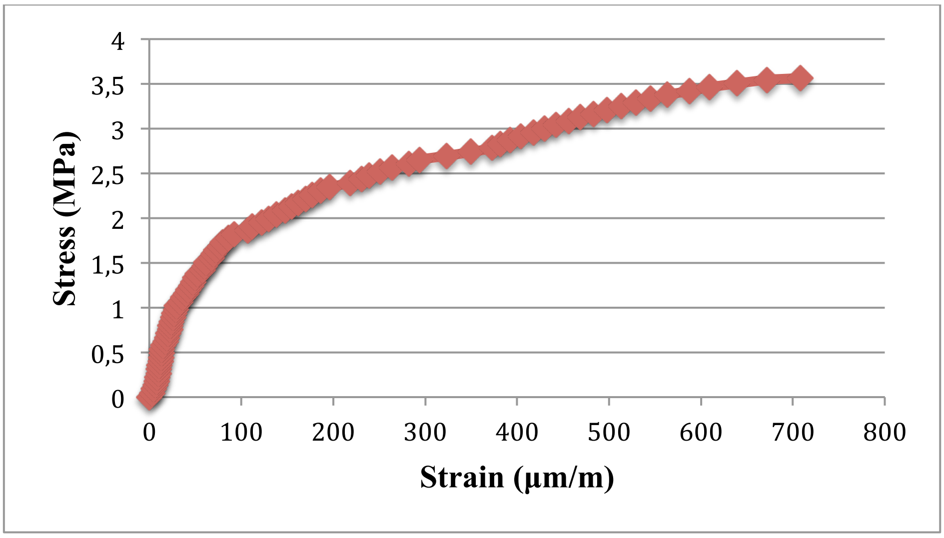

Figure 3.24 Stress strain curve of sample made in the field from campus soil

The UCS for the sample created in the field was 3,57 MPa. Despite using the same soil as in the previous sample, the mixing process and the quantity of cement differed, this one having a small percentage of stabilizer. Also the curing period was done less rigorously and the loss of moisture was bigger than in sample number two.

3.3.3.2. Durability test

For the durability test one block taken from the construction (cut from the prototype wall) was taken and spray tested as stated by IS: 1725-1982 [30] and resumed in 2.6. A shower of 10 cm of diameter and holes of 2 mm of diameter as it can be appreciated in Figure 3.25.

Figure 3.25: Procedure for the durability test

The limiting depth of the pit formed is to be within 10 mm for passing this weathering as per the code specification [30]. The pitting depth obtained was less than 2mm, which confirms the recommendation.

Figure 3.26: Erosion caused to the sample

3.3.3.3. Mineralogical characterization

The mineralogical characterization of the different samples was made using X-Ray diffraction (XRD). This analysis is done to identify the compounds formed in the soil-binder mixtures. From the XRD pattern can be deduced which is the percentage of stabilizer in a material that has not reacted. Additionally, it may be useful to identify the particles non hydrated.

The detector moves in a circle around the sample, then its position is recorded as the angle 2theta (2θ). Every phase has a specific chemistry and atomic arrangement. Normally they produce a particular peak except amorphous materials that does not produce any sharp diffraction peaks.

RE materials are characterized by having high content of Mullite and SiO_2 related to quartz and feldspar in XRD diagram. Lower contents of Al_2O_3 and K_2O are founded, related to clay minerals and alkali feldspar. It is expected also to have relatively high LOI is founded also due to the release of OH^- from clays and CO_2 from calcite [43]. Hydration compounds such as CSH and CASH will be also found, as well as Portlandite, result of cement hydration. The stabilization process will have also an effect on XRD patterns, reducing the quartz peaks while increasing the cementitious element [44].

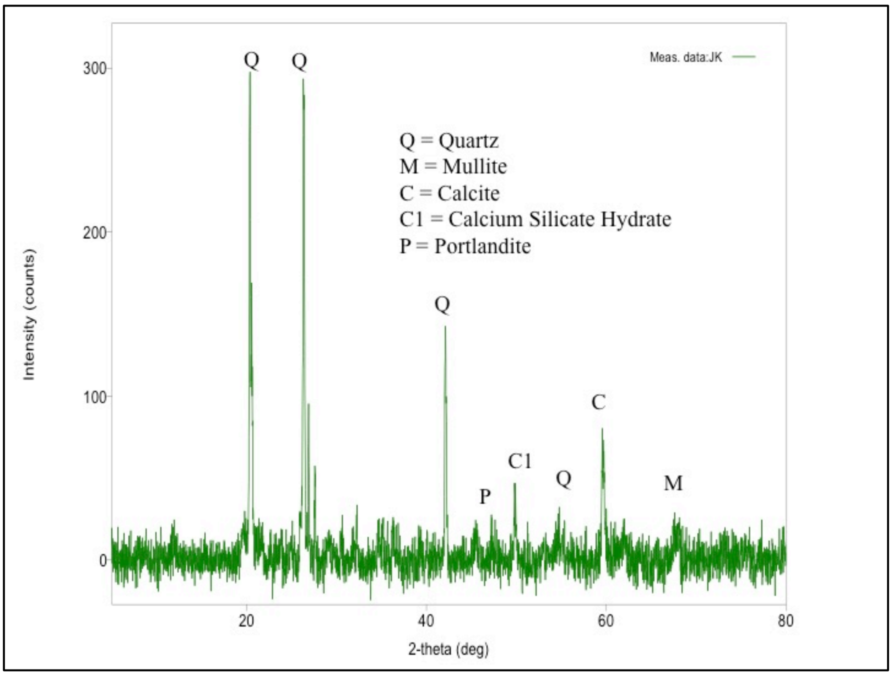

Figure 3.27: XRD analysis for Dewgain soil

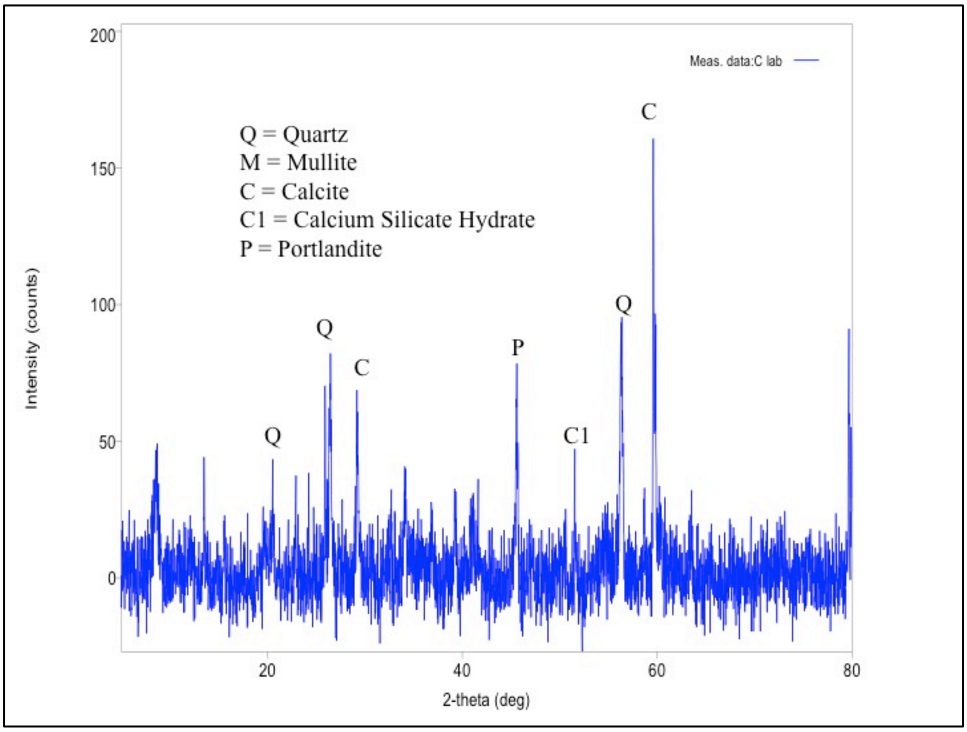

Figure 3.28: XRD analysis of Campus soil laboratory sample

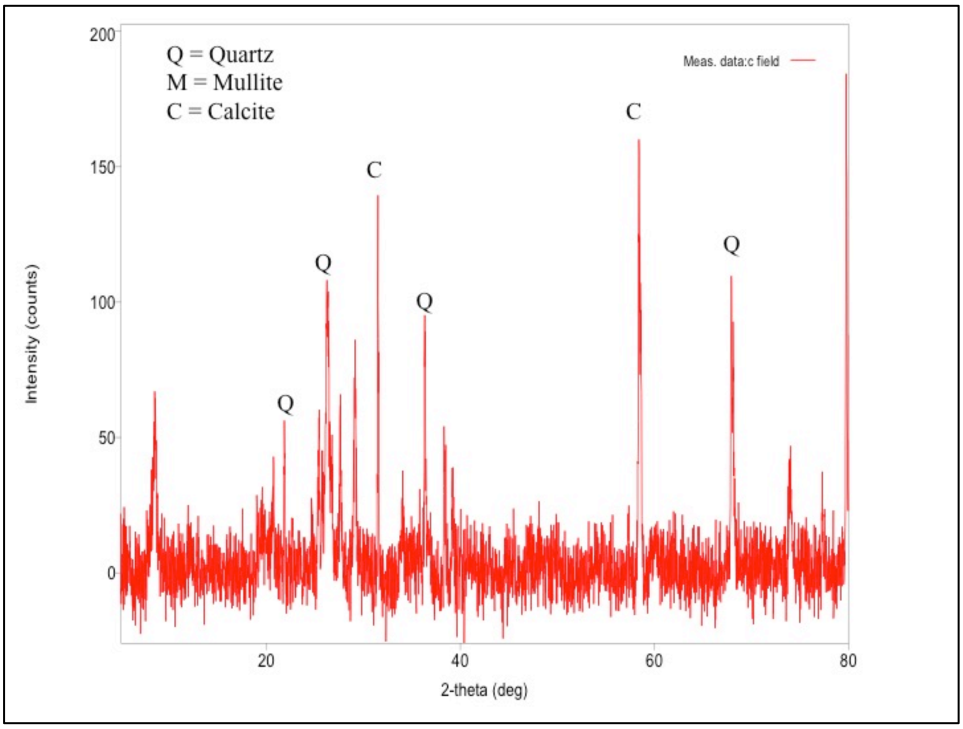

Figure 3.29: XRD analysis of Campus soil field sample

3.3.3.4. Thermal Conductivity of RE

The Thermal Conductivity (k) of the RE used for construction has been calculated using the two slab guarded hot plate method as specified in IS 3346 [45]. The set up for thermal conductivity is shown in Figure 3.30.

Figure 3.30: Thermal conductivity set up

For the measurement of k is required to have a one dimensional heat flow passing to a flat specimen. To do so, two specimens are placed between heating plates and cold plates. By knowing the heat input to the central platter and the temperature between the specimen we can calculate k using the formula:

$$k = \frac{q}{2 \cdot A} \cdot \frac{L}{T_h - T_c}$$

Where: k: Thermal Conductivity of the sample [W/m·K]

q: Heat flow rate in the specimen [W]

A: Metring area of the specimen [m^2]

T_h: Hot plate temperature [ºC]

T_c: Cold plate temperature [ºC]

L: Thickness of the specimen [m]

The thermal conductivity obtained after stabilization was 0,267 W/m·ºC. The lowest temperature that can be achieved with Low Thermal Conductivity Concrete is 0,45-0,54 W/m·ºC [46], meaning that this rammed earth has excellent thermal properties.

3.3.3.5. Thermal efficiency modelling

A thermal simulation of the building efficiency was realized with COMSOL Multiphysics® software. The simulation considered a 2D model consisting of RE walls and a room space filled with air in between, represented in Figure 3.31. Two modules were used to calculate the thermal behaviour of the building in extreme conditions: the heat transfer in solids (for the RE walls) and the heat transfer in fluids (for the air filling the inner room). The dimensions of the walls were the same than in the reality, with the same material characteristics: a density of 1930 Kg/m^3, a thermal conductivity calculated of 0,267 W/m·ºC and a specific heat of 1830 J/Kg·K [13]. The dimensions of the space in between were considered the minimum in the room, with a distance of 10 feet (3,048 m), filled with normal air. The ground and the roof were considered as insulate materials.

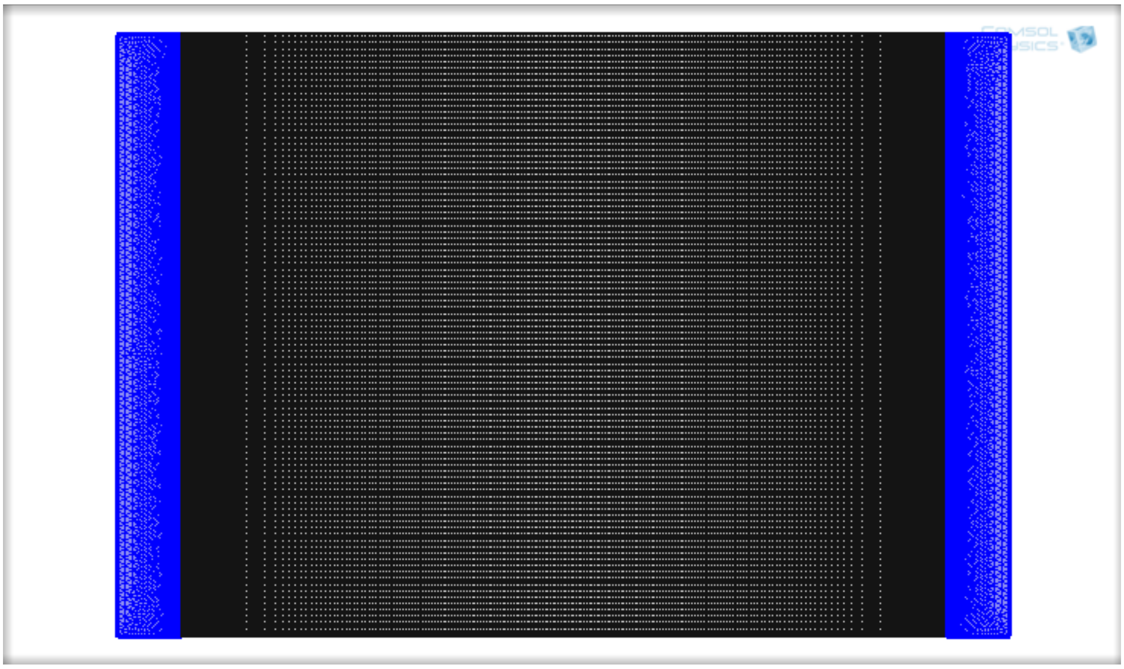

Figure 3.31: COMSOL model with grid and blue representing the walls and black the air

The purpose of the simulation was to determine the fluctuations of temperature in average inside the room in extreme conditions. The hottest day this year was chosen, it was the

09/05/2018, with a maximum temperature of 41ºC and a minimum temperature of 23ºC as represented in

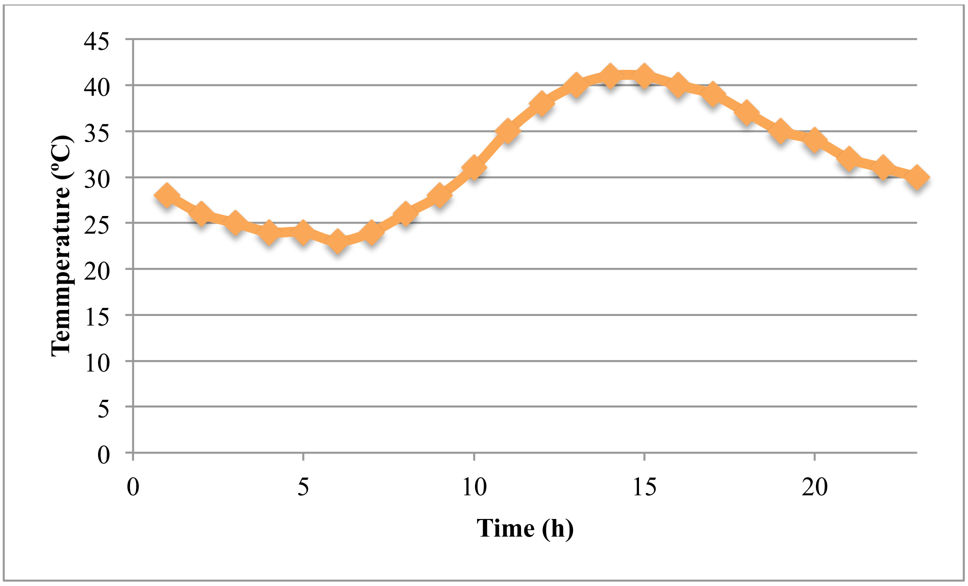

Figure 3.32: Fluctuation of the temperature in the hottest day of the year

The results showed that the temperature inside the room remained constant (Figure 3.33), even if increasing the temperature up to 50ºC.

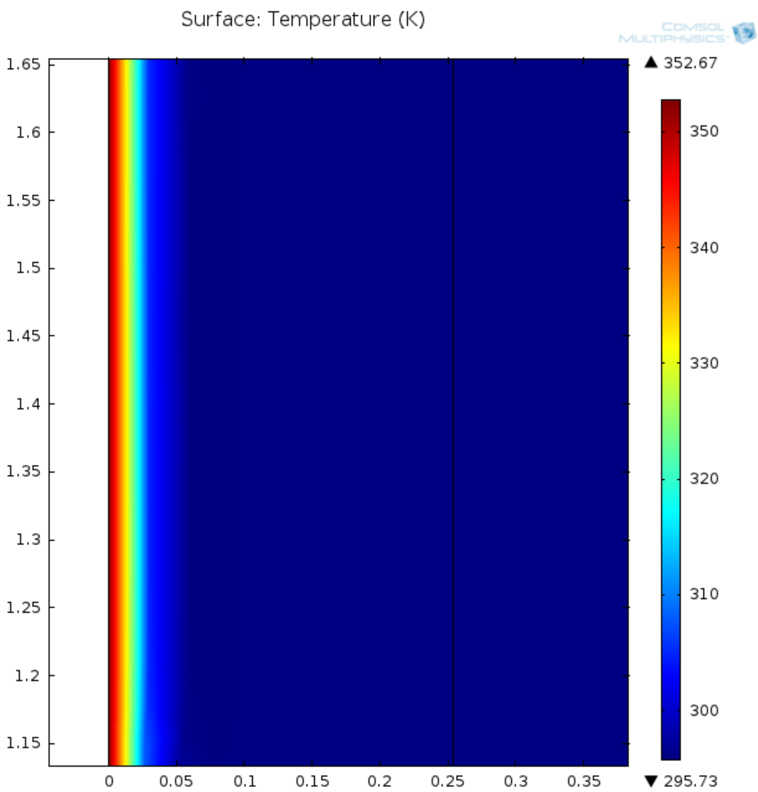

Figure 3.33: Temperature variation through the RE wall

Naturally, the model was supposed not to have windows, which will absorb the sun radiation in some cases increasing the temperature inside. Otherwise, by building a generous and oversized roof this irradiation in summer season can be avoided.

3.4. Prototype Construction

This chapter pretends to resume the experimental process of building a RE house without any previous expertise. Five members composed the working team: 1 Ammachi Labs Staff (Harish Mohan), 1 Brahmachari from Amritapuri (Deva Nath), 2 workers from Ettimadai Amrita University campus and my self. After checking the suitability of the soil and the UCS of the RE walls, the team was prepared to handle with all the challenges during all the process.

3.4.1. Design of the prototype

The purpose of the prototype was to experience the methodology of RE construction through a simple model to then replicate it in form of more complex buildings in villages. It was also a prototype to test all the properties of this material.

For this reason, the building was designed as simply as a unique room with a inner surface area of 10 ft per 12 ft, 120 square foot (11,15 square meters).

The walls were designed with a 10-inch (25,4 cm) thickness, which was a good compromise between thermal properties and labor work. The height of the walls was determined to be 2,4 m, enough to create a proper ventilation inside the room.

3.4.2. Design of the formwork

The design of the formwork must fulfill all the building requirements and adaptations during the construction. It means that the construction method or process must be designed and planned before that. With the aim of reducing the use of material for the formwork, a system using only two formworks was created. The two formworks were attached and the spacers were located at the middle of the shutters, so that when the RE soil reaches the top of the upper formwork, the bottom one can be removed and mounted on the other one. Repeating this process a complete vertical wall can be erected continuously. In that case a vertical wall consists of 8 formwork levels of 30 cm height.

Figure 3.34: Formwork in an upper position

3.4.3. Fabrication of the formwork

The formwork was made adapting a formwork already used by to Ammachilabs[3] to build concrete toilets in rural villages. Holes were drilled in specific positions allowing all the wall construction. Two plaques were welded in order to make the formwork longer and reducing the number of times for assembling and disassembling it. Also some lateral reinforcements were added in order to prevent bending during the ramming process. The complete formwork was composed by 2 small formworks of 30 cm height and 160 cm length assembled vertically. This allowed disassembling the bottom formwork to assemble it in the top of the other one creating a continuous wall as shown in Figure 3.35.

Every formwork was composed by:

- **Shutters:** conformed by mild steel plaques of 5 mm thickness, 30 cm height and 180 cm length.
- **Stiff endings:** Three mild steel T-reinforcements were added equidistant in every shutter to prevent deformation due to high compressing forces.
- **End stops:** Two plywood boards of 5 cm thickness, 240 cm height and 25,4 cm with.

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- **Spacers:** Metal threads of 10 mm of diameter were used as spacers, covered by PVC pipes of 12 mm of diameter and the length equal to the thickness of the RE walls, 25,4 cm.
- **Ties and bolts:** Metal washers and standard bolts were used to fix the spacers to shutters and end stops.
- **T-shape chamfers:** The vertical prominent edges are the most fragile parts of the wall, which remain difficult to ram. The solution proposed was creating mild steel T-shape corners and place them in the corners of the formwork to create chamfers.

After welding all the parts of the formwork it was tested to build one wall of 90 cm height, 160 cm long and 25,4 cm width, with a good result as it can be appreciated in Figure 3.36.

Figure 3.35: Displacement of the formwork during test wall construction

Figure 3.36: Testing wall built in front of the geotechnical lab (Ettimadai campus Amrita University)

3.4.4. Preparation of the site

The chosen site for the prototype construction is located in front of the Ashram as marked in orange in Figure 3.37, as it was an available area and surrounded by nature, which makes the RE house in more harmony with the environment.

Figure 3.37: Location of the prototype in Ettimadai campus of Amrita University

The soil was extracted from a place nearby the Play Ground. As other constructions were going on during vacation time, the soil was already extracted from bellow ground level so we took advantage to take the soil from there and don't involve any extra machinery.

The soil then was sieved to avoid having any big gravel particles as in Figure 3.38. The only big sieve available was 2 mm finer. The process to sieve the soil took 11 days and two people of labor for approximately 15.000 Kg of soil. Using a larger sieve to filter the bigger gravel of 8-10 mm could largely reduce this process.

Figure 3.38: Sieving of the soil next to the extraction site

The next step was the preparation of the site in terms of foundation. The foundations were done using traditional method of stones and mud as shown in Figure 3.39. The dimensions of the foundations were 1foot width (30,48 cm), 1 foot under the ground level and 1 foot above the ground level. Finally, a last layer of concrete of 5 cm thickness was added to level the floor for the walls construction, as in Figure 3.40.

Figure 3.39: Foundation using stones, soil and water

Figure 3.40: Concrete finishing layer for foundations

The soil was then transported by tractors next to the construction site. The transportation cost can be ignored due to the small distance between the soil extraction, sieving site and the construction site.

3.4.5. Machinery and tools used for walls construction

The choice for the wall erection equipment used has been made considering the local available machines next to the site, trying to reduce the costs associated to machinery. That gives sense to RE construction and goes according to its philosophy that is using as maximum as recycled and reused materials for its complete deployment.

3.4.5.1. Mixing

The choice for the mixing machinery was a mild steel concrete mixer of 200 litters capacity. Using this kind of mixer saved a lot of time in the project. Normally this kind of mixers are not advised, yet as the soil is very sandy it can be used in our case [27]. The mixing machine was located near the soil and the constructing place, saving a lot of transportation times during the wall erection as shown in Figure 3.41.

Figure 3.41: Concrete mixing machine used during construction

3.4.5.2. Tampers

Hand rammers were used to compress the earth. As neither pneumatic tampers nor compressor were available in the campus or nearby, the decision was to use manual tampers to reduce machinery costs and research time, as the prototype has reduced dimensions and the further buildings will be done in Dewgain, 2.200 km from Ettimadai campus.

Two types of manual rammers were used as in Figure 3.42:

- Leveling and finishing rammers: Those ones having big surfaces, different shapes and lighter weight. They were used to level the soil before the hard ramming and the finishing part to have a plane surface.

- Power rammers: Two heavy rammers, about 20 pounds (9-10 kg) were used to compress the soil until its maximum compression rate ensuring to have the maximum UCS possible. Those have circular surfaces of 60 mm diameter.

Figure 3.42: Different hand tampers used during prototype house construction

3.4.5.3. Construction supports

Scaffoldings were used as assisting supports in the process of disassembling and assembling the formwork at height, as well as the process of ramming.

A canvas roof was installed during all the construction for two purposes. The first was to protect the workers from the strong sun radiation in afternoon time. The second purpose was to protect the structure from the rain.

Figure 3.43: Scaffoldings and canvas roof used

3.4.6. Walls construction deployment

The first step in the construction of the RE walls was the positioning and well assembling of the formwork. The alignment and fixation on the concrete layer was essential for the good repartition of charges along all the building. For that purpose horizontal lines were marked on the flat concrete to determinate the initial positioning. After some layers of RE the form gets fixed to the ground due to the big density of the compressed soil. The next step was to oil the inside of the shutters to prevent the soil from sticking to the surface when it was removed. It is recommended to oil the top part when the formwork is almost filled, as the soil will absorb some of the oil when ramming the bottom part.

Figure 3.44: Placement of the formwork

The mixing process started during the positioning and fixation of the formwork. The soil and cement percentages were calculated by volume. The content of cement was 7% in volume. Every badge of soil-cement mixture was prepared using 14 containers of soil and 1 container of Portlant cement, as they have approximately the same bulk density before compacting. The volume of the container was known, so we the mass of soil plus cement was approximately 210 Kg. The dry mixture was prepared introducing first 7 receptacles of soil, then the cement and finally the resting 7. After a proper mixing of approximately 2 minutes, 10 cups of 2 litters of water were added step by step, spreading the water uniformly on all the dry mixture. This represents less than 10% of WC added in mass, but as the soil had small water content it was usually enough. Then the wet mixture was mixed during two more minutes until having a homogeneous mix. The "drop test" (resumed in 2.2.1.3) was performed frequently before adding a new layer inside the form to ensure a good consistency for optimal compaction of the particles. The quantity of wet mixture has to be used 2 hours before mixing the cement; otherwise the compaction will not be done properly because of the cement reactions.

Figure 3.45: Preparing process for ramming. Formwork oiling and mixture process

For the compacting process a first light compacting was executed as in Figure 2.9, just to distribute the soil and level it all along the formwork. Thereupon the soil was compacted hitting the soil with the heavy ram and small surface as in Figure 3.47. By impacting the soil, the particles move trying to scape the pressure into small niches, this creates the interlocking agglomerates where finer particles fill the small interstices. It is important to understand that a high but constant pressure is not enough to create that ramming effect. Instead of having a too powerful rammer, which will put unnecessary pressure to the structure and formwork, it is better to use a lighter tool and realize a high number of impacts.

The locking capacity of the soil depends on the composition of granularity present in the soil. Depending on this composition and quality of the soil, an ideal thickness for RE layer will be defined. For our soil, we determine that a layer of loose soil should not be thicker than 21cm, assuming a CR $\left(Compatciton\ Rate = \frac{thickness\ of\ loose\ soil - thicnkess\ of\ rammed\ soil}{thickness\ of}\right)$ of 0,48, meaning a maximum rammed layer of 11 cm. If the layers poured into the formwork are two thick, the top of the layer will be compacted first, creating a lock assemblage that resists the transmission of the impact to the bottom. Another think to keep in mind is the corners. It is the most delicate part of the wall and has to be rammed insistently, as if they remain open it will be a way of exit for the adjacent particles.

Finally the big flat surface rammers were used to create a smooth and flat layer as in Figure 3.48.

Figure 3.46: Leveling of the loose soil

Figure 3.47: Ramming impact

Figure 3.48: Final ramming for a flat a smooth surface

It is advice not to interrupt for too long the ramming process of one vertical wall. If it happens, a joint will be created between the two layers. If a wall has to be interrupted before the whole wall is done and has to be restarted next day, the previous layer has to get wet before restarting.

To place the windows and the doors after the ramming process, wooden blocks were positioned in the desired layer before initiating the compaction of the soil and they were fixed as in Figure 3.49.

Figure 3.49: Wooden blocks inserted in the RE wall

Figure 3.50: Resumee of the ramming process

3.4.7. Finishing

As a must, it is either unnecessary or non-recommended to plaster the rammed earth walls [11]. This plastering will make the wall non permeable. It is important to let the wall transfer the humidity content and react normally to condensation. In our case we just covered the parts where the soil got stuck with a thin layer of mud to make the wall continuous and smooth.

As per last, when the building was finished, a concrete belt was built on the top of the structure to provide a better repartition of the charges as recommended per Auroville Earth Institute © during our visit in their installations.

3.4.8. Roofing Construction

The roof was built using wood beams above a triangular metal structure. On top of the base structure coconut palm leaves were positioned plied and attached creating a flat surface and on top of that another layer of palm leaves where placed creating a consistent two layer roof.

Figure 3.51: Traditional coconut palm leaves roof

3.4.9. Flooring construction

Ceramic tiling was used to cover the floor, using a mud plastering for joining the tiles.

Figure 3.52: Clay tile floor method

3.4.10. Timings

During the house building, we realized that the time spent on moving the formwork would be the most important one in the project. Here bellow the timings of the project are split in order to calculate the costs and have a reference of the timings for future projects:

Sieving

For the sieving two workers were doing the work during 5 days. They were paid at a rate of 800 INR per day (8h working time).

Foundations

For the foundations specified in 3.4.4, two workers were needed during 3 complete days.

Ramming of the walls

The ramming of the walls was done in 11 days. Normally every wall was erected in one day, unless sometimes errors and problems occur during construction, which delayed the work. The work was planned for 8 days, yet the lack of experience and mistakes in the planification added those 3 extra days. Nevertheless, the costs related to that were split in two types of workers: the campus workers, paid at 800 INR per day and the other three volunteer workers (including myself) counted as paid at 350 INR per day.

Finishings

The concrete belt of the wall, roofing, flooring and the installations of windows and door took another total of 5 days for two workers job.

A total of 17 days were needed to finish completely the house, considering that some tasks were done in parallel. This work is not a reference for speeding, as the process was based on trial and error. The weather condition, health of the workers and reliability on machines and tools played an important role in the timings.

3.4.11. Construction costs

It is necessary to describe the financial aspect of the work process, even if it can vary considerably, given the versatility of choices in terms of equipment, tools and team involved.

The following table illustrates what we have spent in our case. Normally there is an initial investment in machines and equipment that has to be managed. In our case it is nonexistent, as we used machinery normally used in construction of the campus, the formwork was constructed with reused materials and the rammers were taken from laboratories.

A) MATERIALS	
23 Bags Ordinary Portland Cement	8.050,00 INR
Stones for the foundation	7.600,00 INR
Door and windows	20.000,00 INR
Roof Materials	4.000,00 INR
Floor clay tiles	2.000,00 INR
Total Materials	**41.650,00 INR**
B) LABOUR	
Sieving	8.000,00 INR
Foundation	4.800,00 INR
RE Walls	25.300,00 INR
Roof,Floor & finishings	8.000,00 INR
Total Labour	**38.100,00 INR**
TOTAL COST PROTOTYPE	**79.750,00 INR**

The rate per square meter of this RE construction (only walls) including materials and manpower is 3588 INR, 44,5 EUR or 52 USD.

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4. Results analysis

The results and their analysis are presented in this chapter and discussed. Initially the summary of the results is presented in the following table and the details of the tests are presented in the ANNEX A. Then the results are analysed particularly one by one to compare with the expected ones and the standards. Finally the non-numerical tests are presented and linked to the previous analysis only for the soil used for the prototype, the campus soil.

Type of soil	Cement	Dry density (g/cm^3)	OMC (%)	UCS in prism (MPa) 28 days	Thermal conductivity (W/m·K)
Dewgain	8%	1,91	12,61	1,41	-
Campus	7%	1,93	10,25	4,02	0,267

Table 4.1: Summary of the numerical key results

4.1.MDD and OMC

The MDD and OMCs were estimated using the Mini Compaction proctor test. The MDD was calculated dividing the mass by the volume of the small cylinder and determining the moisture of the sample. It can be observed that even if the Dewgain soil analyzed have a higher content of finer particles, the MDD is practically the same than for Campus soil, which has a higher coarser content. In both cases the MDD is in the standard range of 1,7-2,2 g/cm^3 [24]. On the other hand the campus soil requires a smaller percentage of moisture to acquire this MDD, possibly because the lack of gravel coarser in this soil that facilitates the interlocking of other particles with less lubrication. For both soils, the OMC decreased by increasing the cement content. This is probably because its finest texture enables the particles to achieve the maximum compaction with less water absorption.

4.2.Unconfined compressive strength

Although with the UCS for small cylinder samples the average UCS obtained for Dewgain soil (with 30% of added sand and 8 % of cement content) was 3,73 MPa, in the Univesal testing machine it only achieved 1,41 MPa. In this case the sample do not pass the minimum of 2 MPa, which is the minimum demanded by the standards. The aspect of the sample before its test (Figure 4.1: Dewgain prism samplebetrayed the non-cohesion between the soil particles and a high porosity in the prism structure. That could be caused by many reasons.

The first one is a not proper pre-treatment of the soil before mixing by breaking the lamps. The second one could be a poor mixing with cement and water due to its high content in finer particles, which makes this process more complicate. The lack of soil in the Amrita University laboratory facilities made impossible to create more samples to corroborate this result. With the high MDD of this mixture, the sample is supposed to have a greater UCS result. Conversely, other options of stabilization can be studied for this particular soil given its particle distribution.

Figure 4.1: Dewgain prism sample

On the other hand, the Campus soil, with less cement content had a UCS of 4,01 MPa. The samples had a more compacted aspect even if they had some surface parts torn because of the disassembling of the mold (Figure 4.2). The UCS could be greater if the sieving of the soil previous to mixing would be done less restrictively. Larger particles coarser than 5-10 mm should be sieved out because they can induce the structure of the wall to have voids. Otherwise, gravel particles between 2-4 mm can strengthen the structure by increasing the interlocking of big particles.

Figure 4.2: Campus prism sample

4.3.Mineralogical composition

The mineralogical characterization using X-Ray Diffraction (XRD) confirms the suppositions made on the UCS samples. In the Dewgain sample quartz (Q) and Mullite (M) are found in majority and high intensity (Figure 3.27), which corresponds to elements that can be found in raw soil. The high intensity of quartz denotes a more amorphous phase of crystal that is related to less reactivity. It contains calcite that confirms the presence of stabilizer, yet in lower measure. Furthermore, the presence of Calcium Silicate Hydrate confirms the hydration compounds with stabilizer and also Portlandite corresponding to the precipitation of cement.

In the prism sample created in the lab the mixture has been done properly. This can be determined as less intensity for quartz (Q) was found, corresponding to raw soil and to a phase less amorphous of the crystal meaning more reactivity. Also higher content of hydrates such as Calcium Silicate Hydrate and Calcite exhibit a better bounding between stabilizer and soil particles (Figure 3.28). The precipitate of cement can also be found in form of Portlandite.

For last, the sample analyzed of campus soil from the field shows also highest rates of raw soil in form of quartz but also higher intensities of calcite than in the Dewgain sample (Figure 3.29).

4.4.Thermal performance

The thermal conductivity calculated after 6 hours of test using the two slab hot plate method (3.3.3.4) has been 0,267 W/m·K. This is a low value compared to normally values of 0,5-1,2 W/m·K for RE. This value is greater than the k for loam, that is between 0,18 and 0,2 W/m·K [11], yet far from the 1,3-1,7 W/m·K for concrete and also less than the 0,45-0,54 W/m·K values for low conductivity concrete.

From the COMSOL Multiphysics® it has been obtained no variation of temperature inside the building for the thermal conductivity obtained, even simulating the hottest day of the year. On the other hand, the suppositions per simulation didn't include windows and was in contact with the outdoor only through the walls.

4.5.Durability

The durability test has demonstrated the resistance to water erosion of SRE walls. The erosion due to the water impact has been minimal and it didn't event reach 20% of the limit as per standard [30]. This demonstrates that waterproofing coat is not required for this type of structures.

4.6.Financial analysis

The rate per square meter of RE has been 3588 INR. The rate for concrete construction is 5000 INR per square meter, almost 40 % more expensive in this zone.

The main consideration about the construction expenses is that the manpower costs increased the cost of the building. This labour time can be reduced rapidly by two ways:

- Investing more time in the designing and building of the formwork to optimize the dismantling and mounting times and avoiding work stoppages.
- Financial investment in a pneumatic rammer system to decrease the tamping time by two or three times.

5. Conclusions and further research

5.1.Conclusions

The conclusions can be separated in different points, as the project approach different aspects, social and technical, yet all pointing to RE solution.

Firstly, from the review of the RE material properties and technique for construction it can be subtract that despite the numerous reports, books and publications during the last years, the understanding of this technique, as well as the design and construction procedure are still far less than other options such as concrete and steel. The reason may be the particularity of each soil has an incidence in the results. Therefore, the best practice is experimenting in laboratories through several tests proposed to determine the suitability and the best binder mixture determination.

Secondly, after obtaining the soil properties through standard testing, we can conclude that soil from the desired construction site in Dewgain can be suitable for RE construction via stabilization, due to its high content in finer particles that can cause problems of shrinkage and may difficult its compaction. The results of UCS indicate that this soil has not an acceptable strength while using cement for its stabilization. Other options must be studied such as lime, which may match better with this specific silky soil.

Thirdly, the prototype built in the Ettimadai Campus of Amrita Vishwa Vidyapeetham has provided experience to workers and technical staff, being for this institution the first building erected using this technique. The experience constructing with technique is limited around the world and especially in India, which is concentrate in Auroville, Tamil Nadu. Lack of professional experience designing and building with earth can have influence in several aspects such as the moisture sensitivity, shrinkage or cracking problems or even a high timing construction with consequence increase on the building cost. From the experience we can emphasize in the importance of an investment in time design and adequate materials for the formwork fabrication, since it has a relevant influence in the construction work time and quality of the material and finishing.

For last, the implementation of RE buildings in Dewgain village will have numerous advantages respect the actual methods used nowadays, being separated in four domains: health, society, environment and economy.

Regarding the health and comfort, RE technique result in having a thermal stability along the year in this zone. The high fluctuations of the temperature are not supposed to have an impact in the inner parts of the building because of its natural thermal conductivity, as demonstrated by simulation. The material is fireproof because of the earth content and has been demonstrated that stabilized is also resistance to extreme water conditions. In addition is resistant to thermite attacks because of its high compaction.

Socially, the RE does not represent a big contrast with the actual vernacular, culturally valuable and responsible mud technique currently used. This improvement on the actual technique will reduce the maintenance timings as well as the building performance, to increase the value through the lens of social perception about having earth houses.

Environmentally, we have been experienced beyond the literature, that RE involves very few resources, plus the necessary tools and materials can be found in the nature or recycled. This represents a responsibility with the nature and resources, which are becoming rapidly limited.

Economically, it has been demonstrated that building with RE even without having any experience is less costly than current techniques as concrete. As the workmanship represents the most important part of the budget, this difference will be even more important in zones where the labor costs are more affordable.

For all these reasons RE represents the best option beyond actual techniques applicable by the government such as concrete, bricks and stone.

5.2.Recommendations for further research

As only the building prototype has been done in the campus by Live-in-Labs program, then further work is to be continued, this section indicates the future directions to point out what should be the next steps for the project:

- The prototype has to be used to extract the maximum data as possible to predict behaviors in its application in Dewgain village. This includes a monitoring of the temperatures inside and outside the house to corroborate the simulations realized. Also a regular structure appearance analyze via media (photos, videos) will be useful to detect any issues and spot the origin.
- A deepest research about the best binder solution for Dewgain village soil has to be done. Investing some time making UCS test with different stabilizers and proportions might avoid the need of additional sand to make the soil suitable for RE construction.
- Formwork design. The application of this technique in Dewgain needs a proper formwork design and fabrication. Some materials are available in Dewgain from the last concrete toilet construction. They can be reused but modified in order to support the high pressures of RE process.
- Roof design. Some solutions have been described from literature. It is one of the main challenges to design of a roof in concordance with RE walls. In order to make the building well thermal performing as well as to reduce the leakage and maintenance.
- Search for financial founds. Jharkhand government has been investing to build new concrete houses in that area. The RE solution can be proposed to change the directions of materials used nowadays.
- Community participatory approach. This is the key of success for this project. This method should be not only implemented by external organizations of the village but always taking the participation of the whole community. The community will be the final user, the beneficiary and even the operator. For that, a methodology needs to be designed to teach them how to build their own buildings using this technique and empower them to be the actors of their own development.

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ANNEXURE

ANNEXURE A: SURVEY REALIZED IN DEWGAIN VILLAGE

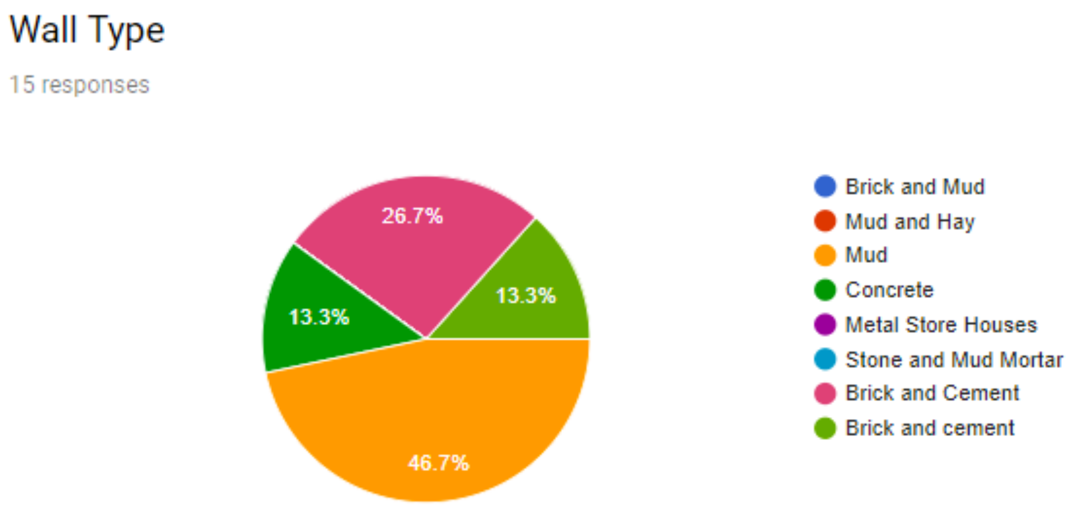

Figure A.0.1: Wall type usage in Dewgain village

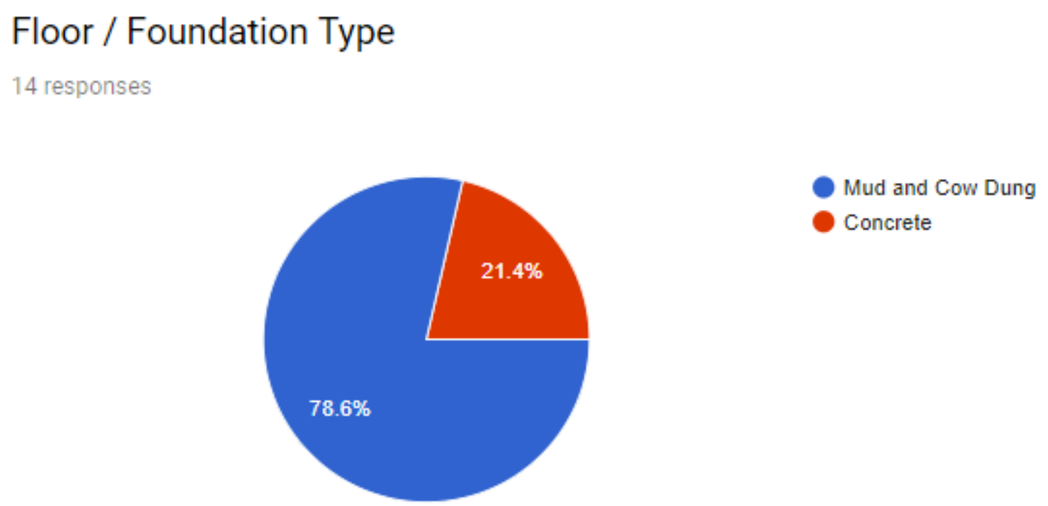

Figure A.0.2: Floor type usage in Dewgain village

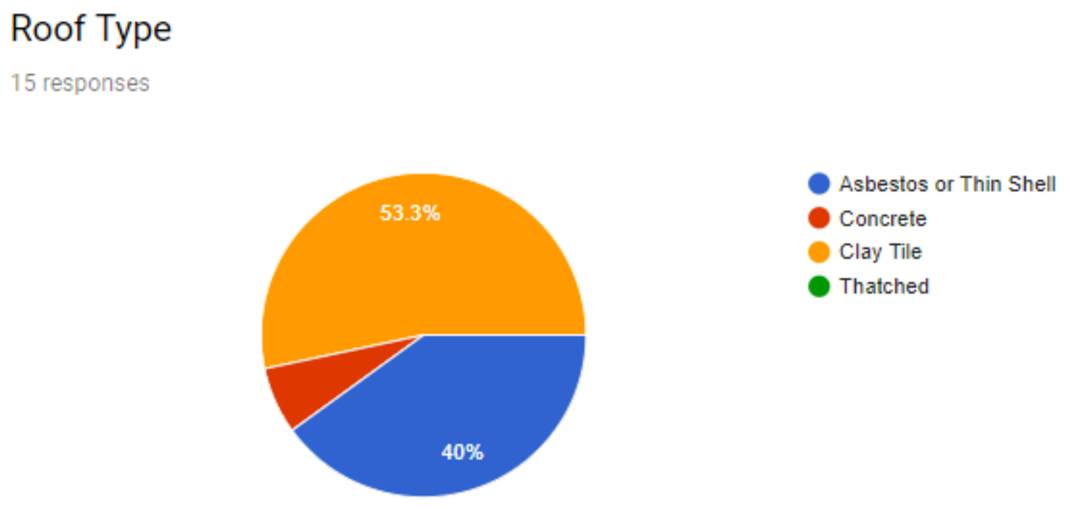

Figure A.0.3: Roof type usage in Dewgain village

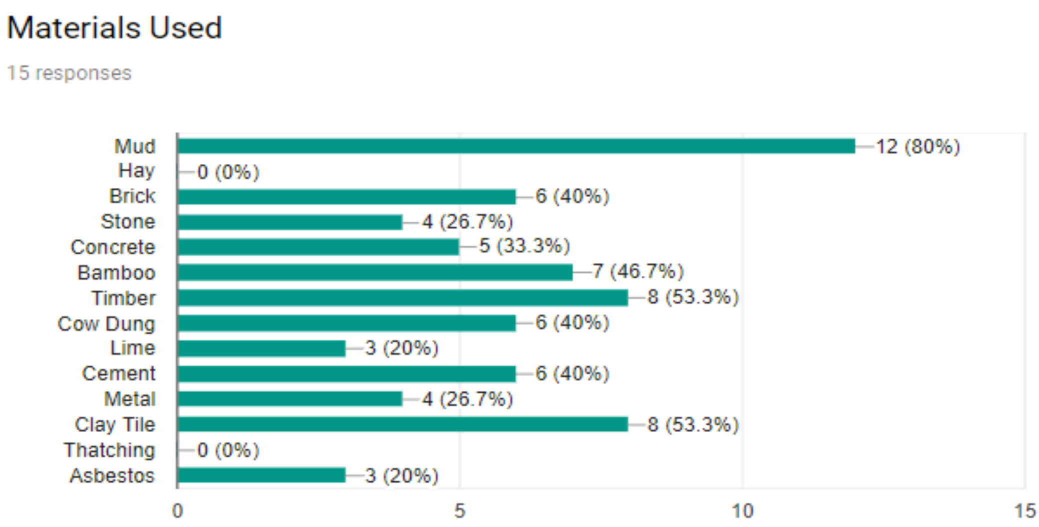

Figure A.0.4: Material usage in Dewgain village

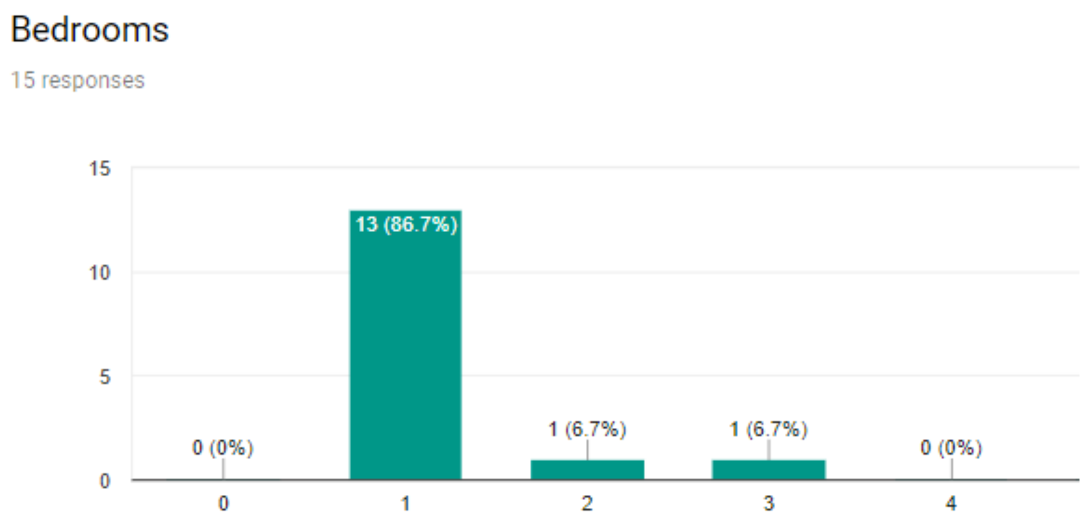

Figure A.0.5: Number of bedrooms in Dewgain village houses